(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 498 375 A1**

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number: 92101834.7

(22) Date of filing: 03.02.92

(51) Int. Cl.5: G02F 1/21, G02F 1/1333, H01S 3/106

(30) Priority: 04.02.91 JP 13414/91
15.07.91 JP 174164/91
11.11.91 JP 294673/91

(43) Date of publication of application:
12.08.92 Bulletin 92/33

(84) Designated Contracting States:
DE FR GB NL

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(54) Electrically tunable wavelength-selective filter.

(57) A tunable wavelength-selective filter including a glass substrate (48A), a transparent electrode layer (45A), a high reflective mirror (44A), an alignment layer (43A), a liquid crystal layer (41), an alignment layer (43B), a transparent material layer (42) whose refractivity index is substantially equal to that of the liquid crystal layer (41), a high reflective mirror (44B), a transparent electrode layer (45B), and a glass substrate (48B), which are stacked in this order. An etalon cavity of the filter includes two layers, the liquid crystal layer (41) and the glass plate (42) as a transparent material layer, which enables to lengthen the cavity length without increasing absorption and scattering of the cavity. This makes it possible to narrow FWHM, quicken the response time, and increase the transmittance of the filter. As applications of the filter, a double cavity structure tunable wavelength-selective filter of a wide tunable range, and a photodetector of a simple construction can be realized.

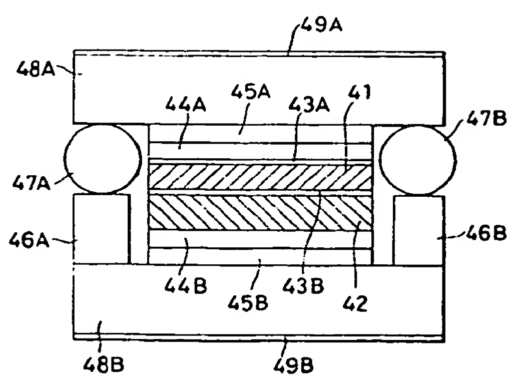

FIG.4A

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The present invention relates to an electrically tunable wavelength-selective filter whose resonance wavelength is variable so that it can select a desired optical signal of an intended wavelength from wavelength division multiplexed optical signals transmitted through an optical fiber.

Optical fiber communications have increased at a rapid rate recently, because of their tremendous information carrying capacity. The current optical communications, however, transmit only a coded pulse stream ignoring wavelength information. Transmission of many optical pulse streams of diverse wavelengths might further increase information carrying capacity. This technique is termed wavelength division multiplexing (WDM), and has been intensively studied. In the wavelength division multiplexing, a tunable wavelength-selective filter is needed that can select an intended optical signal from a great number optical signals of different wavelengths. In particular, a filter is required having a narrow bandwidth, a wide tunable range, and a low loss.

As conventional type filters of this kind, there are a grating monochromator whose grating is controlled by a motor, an etalon whose resonator length is controlled by a piezoelectric cell, a semiconductor optical waveguide tunable wavelength-selective filter including a Bragg reflector, and a planar light wave Mach-Zehnder interferometer formed on an Si substrate. Each of them, however, has their own disadvantages: the grating monochromator or the etalon becomes a bulky module because they are mechanically controlled; the semiconductor optical waveguide filter has only a narrow tunable range; and the Mach-Zehnder interferometer must be connected in a number of stages in cascade, and further requires a complicated control system.

To eliminate the disadvantages of the mechanical filters or the semiconductor optical waveguide filter, we proposed a tunable liquid crystal wavelength-selective filter. It includes a liquid crystal contained in a Fabry-Perot interferometer, and its optical length can be varied by applying a voltage (Japanese Patent Application No. 2-71901, 1990).

A tunable liquid crystal wavelength-selective filter is characterized by such features as small size, low driving voltage, and low cost.

Fig. 1 is a cross-sectional view illustrating an arrangement of a conventional tunable liquid crystal wavelength-selective filter. It comprises a liquid crystal 1 sandwiched between alignment layers 3A and 3B, dielectric mirrors 4A and 4B, transparent electrodes 5A and 5B, glass substrates 8A and 8B, and antireflection coat (AR) 9A and 9B. Its cavity gap, that is, the distance between the two dielectric mirrors 4A and 4B is a few micrometers to an order of ten micrometers. The liquid crystal 1 is a nematic liquid crystal, and its molecules are aligned parallel to the surface (homogeneous ordering).

Typical characteristics of the common structure filter are as follows: the bandwidth is approximately 0.3-0.6 nm; loss is 2-3 dB; tunable range is about 50-100 nm; and finesse is 150-250. In an etalon filter, a range five times the bandwidth gives an extinction ratio of about 20dB, and hence, wavelength spacing of 2 nm enables the filter to be applied to a 50 wavelength division multiplexing. Application to frequency division multiplexing (FDM), however, requires a bandwidth equal to or less than 0.1 nm in practice. The bandwidth can be narrowed by increasing the cavity length of an etalon filter. A cavity gap of 70 μm, for example, gave a bandwidth of 0.1 nm and a tunable range of 10 nm, although it caused a problem that its loss increased to 10 dB. In addition, 70 μm cavity gap remarkably delayed the response time to an order of several tens of seconds.

Furthermore, the tunable liquid crystal wavelength-selective filter has another disadvantage that it exhibits polarization dependence. In other words, although it operates as a tunable wavelength-selective filter for light whose polarization direction is parallel to liquid crystal molecules, it cannot operate for light whose polarization direction is perpendicular to the liquid crystal molecules.

Table 1 comparatively shows characteristics of the above-mentioned tunable wavelength-selective filters. All the filters have a limited number of selective channels from several tens to one hundred, and hence, a narrower bandwidth and a wider tunable range are required.

TABLE 1

CHARACTERISTICS OF TUNABLE WAVELENGTH-SELECTIVE FILTERS				
Filter	Bandwidth (GHz)	Tunable Range (nm)	Loss (dB)	Selective Number
1	< several tens	> 100	1-2	100
2	10	3	10	10
3	5	10	3-5	128
4	38	30	3	Several tens
5	60	140	2	50

NOTES:
1: mechanical grating monochromator
2: semiconductor filter
3: waveguide Mach-Zehnder interferometer
4: mechanical fiber Fabry-Perot Interferometer
5: liquid crystal filter
125 GHz corresponds to 1 nm.

Incidentally, the tunable liquid crystal wavelength-selective filter is described in the following articles:

(1) Masashi HASHIMOTO "An Optical Resonator type Wavelength Selector Using Liquid Crystal (2)", 1986, Japan.

(2) Stephen R. Mallinson "Wavelength-selective filters for single-mode fiber WDM systems using Fabry-Perot interferometers", APPLIED OPTICS, Vol. 26, No.3, 1 February 1987.

(3) M.W.Maeda, et al. "Novel Electrically Tunable Fiber Based on a Liquid-Crystal Fabry-Perot Etalon for High-Density WDM Systems", ECOC '90-145.

(4) M.W.Maeda, et al. "Electronically Tunable Liquid-crystal-Etalon Filter for High-Density WDM Systems", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 2, NO.11, NOVEMBER 1990.

On the other hand, the wavelength division multiplexing requires a photodetector that has a tunable wavelength-selective function so that an intended optical signal is selected from a number of optical signals of different wavelengths.

Figs. 2 and 3 illustrate conventional photodetectors with a tunable wavelength-selective filter.

In Fig. 2, an intended wavelength is variably selected by adjusting an angle of a grating 21. Reference numeral 22 designates a lens. To improve the resolution, it is necessary to elongate the distance between an incident fiber 24 and a photodetector 23, which makes the set large. In addition, it is fragile against mechanical shocks.

To eliminate these disadvantages, a photodetector as shown in Fig. 3 is proposed. It comprises a tunable liquid crystal wavelength-selective filter 35 having liquid crystal retained in a Fabry-Perot interferometer. Reference numerals 38 and 39 denote birefringent prisms and $\lambda/2$ plates, respectively. This photodetector has advantages in that it is small in size, uses low driving voltage, and is low cost. In addition, since it is solid state, it is strong against mechanical shock. However, it requires a considerable effort for fiber coupling alignment because single-mode fibers 34 are connected to both ends. Further, it costs much because birefringent prisms 38 or polarization beam splitters as their alternatives are needed at the input side and the output side.

Accordingly, it is an object of the present invention to provide an electrically tunable wavelength-selective filter having a cavity of reduced absorption and scattering so that it can achieve high transmittance and narrow FWHM (Full Width at Half Maximum) so as to be applied to frequency divided multiplexing in a 1.3 - 1.55 μm band.

Another object of the present invention is to provide a tunable wavelength-selective filter whose bandwidth is narrow such as less than 0.1 nm, and whose tunable range is wide such as greater than 100 nm.

Still another object of the present invention is to provide a polarization-independent photodetector of a simple structure that can variably select a desired wavelength.

In a first aspect of the present invention, there is provided an electrically tunable wavelength-selective filter comprising:

a first glass substrate;

a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of the liquid crystal layer;
a second high reflective mirror;
a second transparent electrode layer; and
a second glass substrate;
which are arranged in this sequence.

Here, the transparent material layer may be a glass plate.

The thickness d_1 of the liquid crystal layer and a thickness d_2 of the glass plate may satisfy a condition that a ratio d_2/d_1 falls in a range from 0.8A to 1.2A inclusive, where

$A =$ $0.75(n_e - n_o)m/n_e - 1$,
$m =$ $2n_e(d_1 + d_2)/\lambda m$,
n_e is an extraordinary refractive index of the liquid crystal,
n_o is an ordinary refractive index of the liquid crystal, and
λm is a transmission peak wavelength.

The transparent material layer may be an organic polymer layer.

In a second aspect of the present invention, there is provided an electrically tunable wavelength-selective filter comprising:

a first tunable liquid crystal wavelength-selective filter; and
a second tunable liquid crystal wavelength-selective filter which is stacked on the first tunable liquid crystal wavelength-selective filter;
the first tunable liquid crystal wavelength-selective filter including:
a first glass substrate;
a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a first liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of the liquid crystal layer;
a second high reflective mirror;
a second transparent electrode layer; and
a second glass substrate;
which are arranged in this sequence,
and the second tunable liquid crystal wavelength-selective filter including:
a third glass substrate;
a third transparent electrode layer;
a third high reflective mirror;
a third alignment layer;
a second liquid crystal layer;
a fourth alignment layer;
a fourth high reflective mirror;
a fourth transparent electrode layer; and
a fourth glass substrate;
which are arranged in this sequence.

The transparent material layer may be a glass plate or an organic polymer layer.

The first tunable liquid crystal wavelength-selective filter and the second tunable liquid crystal wavelength-selective filter may be stacked in such a manner that they are inclined each other.

The first tunable liquid crystal wavelength-selective filter may have a longer cavity gap than the second tunable liquid crystal wavelength-selective filter.

In a third aspect of the present invention, there is provided a photodetector comprising:

an input optical fiber;
lensing means for collimating light transmitted through the input optical fiber;
a fiber connecting portion connecting the input optical fiber to the lensing means;

polarization beam separation means for polarization separating the light transmitted through the lensing means into a first polarization light beam and a second polarization light beam;

polarization rotation means for rotating polarization of the second polarization light beam;

an electrically tunable liquid crystal wavelength-selective filter selectively transmitting the first and second polarization light beams;

a focusing lensing means for focusing the first and second polarization light beams transmitted through the electrically tunable liquid crystal wavelength-selective filter; and

photodetecting means for detecting the first and second polarization light beams focused by the focusing lensing means,

wherein the electrically tunable liquid crystal wavelength-selective filter includes:

a first glass substrate;

a first transparent electrode layer;

a first high reflective mirror;

a first alignment layer;

a liquid crystal layer;

a second alignment layer;

a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of the liquid crystal layer;

a second high reflective mirror;

a second transparent electrode layer; and

a second glass substrate;

which are arranged in this sequence.

The polarization rotation means may be a $\lambda/2$ plate.

The polarization rotation means may be a $\lambda/4$ plate and a mirror.

The polarization beam separation means may comprise a polarization beam splitter and a prism.

The polarization beam separation means may be a birefringent plate.

The polarization beam separation means may incline the incident beam with regard to the tunable liquid crystal wavelength-selective filter.

The photodetecting means may be a PIN photodiode or an avalanche photodiode.

The photodetector may further comprise a multimode optical fiber disposed between the focusing lensing means and the photodetecting means.

In a fourth aspect of the present invention, there is provided a photodetector comprising:

an input optical fiber;

lensing means for collimating light transmitted through the input optical fiber;

a fiber connecting portion connecting the input optical fiber to the lensing means;

polarization beam separation means for polarization separating the light transmitted through the lensing means into a first polarization light beam and a second polarization light beam;

polarization rotation means for rotating polarization of the second polarization light beam;

an electrically tunable liquid crystal wavelength-selective filter selectively transmitting the first and second polarization light beams;

a focusing lensing means for focusing the first and second polarization light beams transmitted through the electrically tunable liquid crystal wavelength-selective filter; and

photodetecting means for detecting the first and second polarization light beams focused by the focusing lensing means;

wherein the electrically tunable liquid crystal wavelength-selective filter includes:

a first tunable liquid crystal wavelength-selective filter; and

a second tunable liquid crystal wavelength-selective filter which is stacked on the first tunable liquid crystal wavelength-selective filter,

the first tunable liquid crystal wavelength-selective filter including:

a first glass substrate;

a first transparent electrode layer;

a first high reflective mirror;

a first alignment layer;

a first liquid crystal layer;

a second alignment layer;

a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of the liquid crystal layer;

a second high reflective mirror;

a second transparent electrode layer; and
a second glass substrate;
which are arranged in this sequence,
and the second tunable liquid crystal wavelength-selective filter including:
a third glass substrate;
a third transparent electrode layer;
a third high reflective mirror;
a third alignment layer;
a second liquid crystal layer;
a fourth alignment layer;
a fourth high reflective mirror;
a fourth transparent electrode layer; and
a fourth glass substrate;
which are arranged in this sequence.

In a fifth aspect of the present invention, there is provided a photodetector comprising:
an input optical fiber;
lensing means for collimating light transmitted through the input optical fiber;
a fiber connecting portion connecting the input optical fiber to the lensing means;
polarization beam separation means for polarization separating the light transmitted through the lensing means into a first polarization light beam and a second polarization light beam;
polarization rotation means for rotating polarization of the second polarization light beam;
an electrically tunable liquid crystal wavelength-selective filter selectively transmits the first and second polarization light beams; and
at least two photodiodes independently detecting the first and second polarization light beams transmitted the electrically tunable liquid crystal wavelength-selective filter;
wherein the electrically tunable liquid crystal wavelength-selective filter includes:
a first glass substrate;
a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of the liquid crystal layer;
a second high reflective mirror; and
a second transparent electrode layer,
which are arranged in this sequence, wherein the electrically tunable liquid crystal wavelength-selective filter and the photodiodes are integrally arranged in such a manner that the photodiodes are arranged on the second transparent electrode layer.

The electrically tunable wavelength-selective filter according to the first aspect of the present invention includes a cavity whose thickness is greater than that of the conventional normal type liquid crystal filter. The cavity is not entirely occupied by the liquid crystal, but comprises the transparent material layer, such as transparent glass, transparent plastics, or transparent organic polymers, having a refractive index equal to that of the liquid crystal. Thus, a filter of a narrow bandwidth, low loss and high response speed can be fabricated. This structure is termed "two layer cavity structure". A filter fabricated as a sample has a cavity gap 70 μm thick, a liquid crystal layer 15 μm thick, a transparent material layer 55 μm thick, and a mirror whose reflectivity is 99%.

The electrically tunable wavelength-selective filter according to the second aspect of the present invention includes a first filter and a second filter, which are stacked. The first filter is the narrow bandwidth filter according to the first aspect of the present invention, and the second filter is a conventional normal type filter having a wide tunable range. The second filter selects a plurality of optical signals in a comb fashion, and the first filter selects one of the optical signals. The second filter of a wide bandwidth and wide tunable range is fabricated by reducing its cavity gap to about 5 μm, and by lowering the reflectivity of the mirrors to about 90%. The first filter and the second filter do not interfere because they are stacked in such a manner that they slope each other slightly.

The polarization independent photodetector according to the third aspect of the present invention includes a tunable liquid crystal wavelength-selective filter, and a polarization beam splitter, a prism and a $\lambda/2$ plate, which are disposed at the input side of the filter. A birefringent prism can be used as an

alternative of the polarization beam splitter and prism. A light beam incident onto the polarization beam splitter transmits in two different path: a first beam whose polarization direction is parallel to the liquid crystal molecules transmits the filter; whereas a second beam whose polarization direction is perpendicular to the liquid crystal molecules is rotated by 90 degrees by the λ/2 plate, and is incident onto the tunable liquid crystal wavelength-selective filter so that the second beam passes the filter. The two beams are mixed by the lens. In this case, since the two beams pass two different points typically 2 - 5 mm apart, the filter will not exhibit polarization independence if the transmission wavelengths of the two points are different. To overcome this problem, each transparent electrode of the filter is divided into two sections and different voltages are applied to the two points through variable resistors so that the transmission wavelengths of the two points are made equal, thus achieving polarization independence.

Another polarization independent photodetector according to the present invention comprises a tunable liquid crystal wavelength-selective filter, and a λ/4 plate and a mirror attached to the input side of the filter. A light beam is incident onto the filter with an angle (typically within 3 degrees). The light beam whose polarization direction is parallel to liquid crystal molecules, and whose wavelength is equal to the resonant wavelength passes the filter. In contrast, the light beam whose polarization direction is perpendicular to the liquid crystal molecules, or whose wavelength is different from the resonant wavelength is reflected. The polarization direction of the reflected light is rotated twice by the λ/4 plate and the mirror so that the polarization direction becomes parallel to the liquid crystal molecules, and is incident again onto the filter. The light beam whose wavelength is equal to the resonant wavelength passes the filter. The two beams are mixed by the lens. Thus, the filter becomes polarization independent. The two beams are usually separated less than 1 mm apart, and hence, the transmission wavelengths of the two beams are identical.

The above and other objects, effects, features and advantages of the present invention will become more apparent from the following description of the embodiments thereof taken in conjunction with the accompanying drawings.

Fig. 1 is a cross-sectional view showing an arrangement of a conventional tunable liquid crystal wavelength-selective filter;

Fig. 2 is a schematic view showing an arrangement of a conventional grating type photodetector;

Fig. 3 is a schematic view showing an arrangement of a conventional polarization-independent photodetector employing a tunable liquid crystal wavelength-selective filter;

Fig. 4A is a cross-sectional view showing an arrangement of a first embodiment of a tunable liquid crystal wavelength-selective filter according to the present invention;

Fig. 4B is a cross-sectional view showing a major portion of the tunable liquid crystal wavelength-selective filter of Fig. 4A;

Fig. 5 is a diagram illustrating the mirror reflectivity dependence of the transmittance of the tunable liquid crystal wavelength-selective filter as shown in Fig. 4A;

Fig. 6 is a diagram illustrating the mirror reflectivity dependence of the finesse of the tunable liquid crystal wavelength-selective filter as shown in Fig. 4A;

Fig. 7 is a diagram illustrating the mirror reflectivity dependence of the full width at half maximum (FWHM) of the transmission peak of the tunable liquid crystal wavelength-selective filter as shown in Fig. 4A;

Fig. 8 is a diagram illustrating transmission spectrum of the tunable liquid crystal wavelength-selective filter as shown in Fig. 4A when no voltage is applied to the filter;

Fig. 9 is a diagram illustrating the shift behavior of the transmission peak wavelengths of the tunable liquid crystal wavelength-selective filter as shown in Fig. 4A when various voltages are applied;

Fig. 10 is a cross-sectional view showing an arrangement of a second embodiment of a tunable liquid crystal wavelength-selective filter according to the present invention;

Fig. 11 is a graph illustrating the applied voltage dependence of the resonant wavelength of the tunable liquid crystal wavelength-selective filter 101 having a two layer cavity structure;

Fig. 12 is a graph illustrating the applied voltage dependence of the resonant wavelength of the normal type tunable liquid crystal wavelength-selective filter 102;

Fig. 13 is a diagram illustrating wavelength selection of the tunable liquid crystal wavelength-selective filter as shown in Fig. 10;

Fig. 14 is a block diagram showing an arrangement of a polarization independent photodetector as a third embodiment of the present invention;

Fig. 15 is a diagram illustrating shift characteristics of the wavelengths of the transmission peaks of the tunable liquid crystal wavelength-selective filter used in the third embodiment when the applied voltage is varied;

Fig. 16A is a diagram illustrating the output characteristic of a photodetector of the third embodiment;

Fig. 16B is a diagram illustrating an input waveform and an output waveform of an optical signal in the third embodiment;

Fig. 17A is a block diagram showing an arrangement of a first variation of the third embodiment as shown in Fig. 14;

Fig. 17B is a block diagram showing an arrangement of a second variation of the third embodiment as shown in Fig. 14;

Fig. 18 is a diagram illustrating the polarization rotation dependence for the polarization independent photodetector as shown in Fig. 17A;

Fig. 19 is a block diagram showing an arrangement of a polarization independent photodetector as a fourth embodiment of the present invention;

Fig. 20 is a block diagram showing an arrangement of a polarization independent photodetector as a fifth embodiment of the present invention;

Fig. 21A is a cross-sectional view of a photodetecting portion of the fifth embodiment; and

Figs. 21B and 21C are perspective views of the photodetecting portion of the fifth embodiment.

The invention will now be described with reference to the accompanying drawings.

EMBODIMENT 1

Fig. 4A is a cross-sectional view showing an arrangement of a first embodiment of a tunable wavelength-selective filter according to the present invention, and Fig. 4B is a schematic view showing a major portion of the filter.

In these figures, reference numeral 41 designates a homogeneously aligned nematic liquid crystal layer; 42, a glass plate as a transparent material layer whose refractive index is substantially equal to that of liquid crystal in the liquid crystal layer 41; 43A and 43B, liquid crystal alignment layers; 44A and 44B, dielectric mirrors as a high reflective mirror; 45A and 45B, indium tin oxide (ITO) transparent electrode layers; 46A and 46B, glass plate spacers; 47A and 47B, spacers; 48A and 48B, glass substrates; and 49A and 49B, antireflection (AR) coats.

Here, the layers 45B, 44B, 42, 43B, 41, 43A, 44A, 45A and 48A are arranged on the substrate 48B in this seguence. Further, the surfaces of the substrates 48A and 48B are covered with antireflection coats 49A and 49B. The distance between the two substrates 48A and 48B is determined by the glass plate spacers 46A and 46B, and the spacers 47A and 47B.

Generally, the characteristics of a normal type etalon can be expressed by the following equations when the etalon includes in its cavity a material causing absorption and scattering.

$$T = Tmax/\{1 + F\sin^2(2\pi mL/\lambda)\} \quad (1)$$

$$Tmax = \{(1-R)^2 \cdot \exp(-\alpha L)\}/\{1-R \cdot \exp(-\alpha L)\}^2 \quad (2)$$

$$F = 4R \cdot \exp(-\alpha L)/\{1-R \cdot \exp(-\alpha L))^2 \quad (3)$$

$$finesse = \pi\sqrt{F}/2 \quad (4)$$

$$FWHM = 2\lambda 0/K\pi F \quad (5)$$

where T is the transmittance of the etalon, Tmax is the maximum transmittance of the etalon, FWHM is a full width at half maximum, λ is the wavelength of incident light, $\lambda 0$ is the resonance wave length, α is absorption coefficient of the cavity, L is a cavity gap, R is the reflectivity of the mirrors, K is $\frac{2L}{\lambda 0}$, and m is an integer.

On the other hand, the characteristics of a two layer cavity structure etalon including the liquid crystal layer 41 and the glass plate 42 in its cavity as shown in Fig. 4A can be expressed as follows when the absorption and scattering of the glass plate 42 is zero.

$$T = Tmax/\{1 + F\sin^2(2\pi mL/\lambda)\} \quad (6)$$

$$Tmax = \{(1-R)^2 B \cdot \exp(-\alpha L)/\{1-R \cdot B \cdot \exp(-\alpha L)\}^2 \quad (7)$$

$$F = 4R \cdot B \cdot \exp(\alpha aL)/\{1-R \cdot B \cdot \exp(-\alpha L)\}^2 \quad (8)$$

finesse $= \pi\sqrt{F}/2$ (9)

FWHM $= 2\lambda 0/K\pi F$ (10)

$B = 4n_1 \cdot n_2/(n_1 + n_2)^2$ (11)

where n_1 and n_2 are refractive indices of the liquid crystal layer 41 and the glass plate 42, respectively, and B is a reflective loss caused by the refractive index difference between the two layers 41 and 42.

Assuming that the cavity gap is 70 µm, the thickness of the liquid crystal layer 41 is 15 µm, and the thickness of the glass plate 42 is 55 µm as shown in Fig. 4B, and that the refractive index of the liquid crystal layer 41 is 1.5296, and the refractive index of the glass plate 42 is 1.50563 (BK7 glass), the mirror reflectivity dependence of the transmittance, finesse and FWHM becomes as illustrated in Figs. 5 - 7. Figs. 5 - 7 also shows the characteristic of the conventional one layer cavity liquid crystal device including liquid crystal layer 70 µm thick. A carve A indicates the characteristic of the two layer cavity structure device according to the present invention, and a curve B indicates that of the conventional one layer cavity device.

As seen from Figs. 5 - 7, the present embodiment can realize FWHM of less than 0.05 nm, and transmittance of greater than 80% by using the two layer cavity structure and the mirrors whose reflectivity is around 99%. The tunable range is about 10 nm, and hence, can satisfy the requirements of frequency division multiplexing. In contrast, the conventional device having a 70 µm thick cavity completely filled with liquid crystal cannot satisfy the requirements of the wavelength division multiplexing because the transmittance falls below 50% when mirrors are used whose reflectivity is around 99%, although the FWHM becomes 0.05 nm. In addition, the 70 µm thick liquid layer will increase the response time to a few seconds to several tens of seconds, though this is not shown in the figures. In contrast, the two layer cavity structure filter has a high speed response time of about several tens of milliseconds.

Next, optimum relationship between the thickness d_1 of the liquid crystal layer 41 and the thickness d_2 of the glass plate (or an organic polymer layer) 42 is described. In the explanation below, n_e is the extraordinary index of the liquid crystal, and n_o is the ordinary index thereof.

The wavelength λm of the transmission peak is given by

$$\lambda_m = \frac{2ne(d_1+d_2)}{m} \qquad (12)$$

and the free spectral range (FSR) is given as

$\lambda_m - \lambda_{m+1} = 2n_e(d_1 + d_2)/m(m+1)$ (13)

The tunable range of the wavelength by voltage application is given by the following approximation:

$$\Delta\lambda \approx \frac{2\Delta n d_1}{m} \times 0.75 \qquad (14)$$

where $\Delta n = n_e - n_o$ is the refractive index difference of the liquid crystal.

Therefore, the optimum condition is achieved when the free spectral range is equal to the shift range, and is expressed as follows:

$1.5\, d_1(n_e\text{-}n_o) = 2n_e(d_1 + d_2)/(m+1)$ (15)

$d_2/d_1 = A = 0.75(n_e\text{-}n_o)(m+1)/n_e - 1$ (16)

Here, since the value m is sufficiently large than 1,

$d_2/d_1 \approx 0.75(n_e\text{-}n_o)m/n_e\text{-}1$ (16)'

For example, when $\Delta n = 0.07$, $n_e = 1.5$, $\lambda = 1.5$ µm and $d_1 + d_2 = 70$ µm, the optimum values are

m = 140, d_1 = 14 µm, and d_2 = 56 µm, and the free spectral range becomes 10 nm. The ratio d_2/d_1, however, need not be exactly A, and is enough if it falls from 0.8A to 1.2A inclusive.

On the basis of the above calculations, the tunable wavelength-selective filter as shown in Fig. 4A was fabricated as follows:

First, bottom surfaces of the synthetic silica glass substrates 48A and 48B whose surface flatness was λ/20 were coated with the antireflection coats 49A and 49B, respectively. Then, the 10-40 nm thick indium tin oxide (ITO) transparent electrode layers 45A and 45B were formed on the top surfaces of the glass substrates 48A and 48B, followed by the formation of the 99% reflectivity dielectric mirrors 44A and 44B on the respective transparent electrodes 45A and 45B.

Subsequently, the 55 µm thick BK7 glass whose surface flatness was λ/20 was attached, as a glass plate 42, to the mirror surface of the dielectric mirror 44B with an adhesive whose refractive index was substantially equal to that of the BK7 glass. Then, a pair of BK7 glasses of the same thickness were attached to the two edges of the glass substrate 48B as the glass plate spacers 46A and 46B. In this case, thickness of the adhesive portion was made less than 1 µm.

After that, the 60 nm thick alignment layers 43A and 43B for the liquid crystal were formed on the dielectric mirror 44A and the glass plate 42 by using a spinner, and were rubbed so that the opposite surfaces were made antiparallel.

Subsequently, the spherical spacers 47A and 47B whose diameters were 15 µm, and which were used for liquid crystal spacers, were bonded to both ends of the glass substrate 48A with an adhesive. After that, the glass substrate 48A on which the layers 45A, 44A and 43A were disposed, and the glass substrate 48B on which the layers 45B, 44B, 43 and 43B were disposed, were bonded via the glass plate spacers 46A and 46B so that the two glass substrates 48A and 48B became parallel. This process was carried out by observing the interference fringes so as to precisely adjust the two glass substrates parallely, and thus, the two glass substrates 48A and 48B were fixed firmly. Finally, the nematic liquid crystal was filled into the cavity formed between the alignment layers 43A and 43B, thereby forming the liquid crystal layer 41. The thickness of the liquid crystal layer 41 was 15 µm. Although, the spherical spacers 47A and 47B are used as spacers for the liquid crystal here, they may be replaced with organic polymer films (e.g., Mylar films) or with fibers.

The spectrum of the thus fabricated liquid crystal-etalon type tunable wavelength-selective filter was observed with an optical spectrum analyzer. This observation was carried out by inputting to the filter a light beam produced by a super luminescent diode having a wide emission spectrum around a 1.52 µm wavelength through an optical fiber, a lens and a polarization beam splitter, and by observing the transmit light with the spectrum analyzer.

Fig. 8 illustrates the transmission spectrum observed: the free spectral range (FSR) around the 1.5 µm wavelength was approximately 12 nm, the FWHM of the transmission peak was 9.1 GHz or 0.07 nm, the loss was 4 dB, and the response speed was 10 msec. Comparing those values with the corresponding values 10 nm, 0.1 nm, 10 dB and a few tens of seconds of the conventional tunable liquid crystal wavelength-selective filter shows that a considerable improvement is achieved.

Fig. 9 illustrates the peak wavelength shift behavior of the tunable wavelength-selective filter when a voltage is applied to the liquid crystal layer 41. The peak wavelength shifts about 12 nm by applying 30 volts to the liquid layer. The FWHM and the transmittance were not affected by the voltage application.

Thus, the tunable wavelength-selective filter of the present invention has narrower FWHM and higher transmittance than those of the conventional liquid-crystal-etalon type tunable wavelength-selective filter, and hence, is preferably applicable to the FDM communications.

Incidentally, although in the present embodiment, a nematic liquid crystal is employed as the liquid crystal layer 41, the liquid crystal layer of the present invention is not restricted to the nematic liquid crystal alone, and any type of liquid-crystal can be used.

In addition, although a part of the liquid crystal is replaced by the thin glass plate in this embodiment, any material can be used as an alternative of the glass plate as long as the material is transparent, and has refractive index substantially equal to that of the liquid crystal. We experienced by using polyimide layer in place of the glass plate. Here, as the polyimide film, FLUPI-01 which was developed by Nippon Telegraph and Telephone Corporation was used (see, Sasaki's article in "Plastic" vol. 42, No. 9, pp. 47-, or Matsumura et al.'s article in "Macromolecule", vol. 24, No. 18, 1991). FLUPI-01 is synthesized from a specific fluorinated diamine including two trifluoromethyl groups and two types of acid anhydrides. The fluorine content of the FLUPI-01 is 31.3%. FLUPI-01 exhibits very high transparency with a loss of 0.3 dB/cm at a 1.3 µm wavelength. Its refractivity is approximately 1.52. A 40 nm thick transparent electrode ITO was formed on a glass substrate coated with antireflection coat, followed by the formation of a dielectric mirror thereon whose reflectivity was 99%. Subsequently, a 55 µm thick FLUPI-01 was formed on the dielectric

mirror with a spinner by using DMAc as solvent, followed by one hour annealing at 350 C°. After that, the filter was arranged in the same manner as the filter using the glass plate. This filter has a free spectral range of about 12 nm around the 1.5 µm wavelength, an FWHM of 0.07 nm, and the transmittance of about 35%.

Thus, using a polyimide film instead of the glass plate as the transparent material layer achieves similar effect. Although polyimide is used as an organic polymer layer in this embodiment, other organic polymers can achieve similar effect as long as they have high transmittance.

The polyimide layer can be formed on the substrate by the spin coating instead of bonding as the glass plate, which facilitates the fabrication.

EMBODIMENT 2

A second embodiment of the tunable wavelength-selective filter according to the present invention is described with reference to Figs. 10 - 13.

Fig. 10 shows an arrangement of the second embodiment. Basically, the second embodiment has a double cavity structure in which a tunable liquid crystal wavelength-selective filter 101 having the two layer cavity structure of the first embodiment is stacked on a normal type tunable liquid crystal wavelength-selective filter 102. The cavity length of the liquid crystal filter 101 is five times longer than that of the liquid crystal filter 102. The filters 101 and 102 are slightly (less than one degree) inclined so that they do not interfere each other.

In Fig. 10, reference numeral 104 designates an adhesive bonding two glass plates 8A and 48B with little loss. The refractive index of the adhesive is substantially equal to that of the glass plates. Reference numerals 105 and 106 denote voltage sources for driving each liquid crystal of the two filters 101 and 102, and 110 denotes a controller determining the voltages of the voltage sources 105 and 106.

Figs. 11 and 12 illustrate the voltage dependence of the resonant wavelength of the two layer cavity structure tunable liquid crystal wavelength-selective filter 101, and that of the normal type tunable liquid crystal wavelength-selective filter 102, respectively. Table 2 illustrates the characteristics of the first filter 101 and the second filter 102. The first narrow bandwidth filter 101 has a narrow bandwidth of 9 GHz or 0.07 nm, a narrow tunable range of 12 nm, and low transmittance of 35%, whereas the second wide tunable range filter 102 has a wide bandwidth of 3.36 nm, a broad tunable range of 127 nm, and high transmittance of 92%. Ten peaks of the first filter 101 are accommodated between the two adjacent peaks of the second filter 102. Thus, several peaks are first selected by the second filter 102 in a comb fashion, and then one of them is selected by the first filter 101. More specifically, by varying the peak wavelength of the wide tunable range filter 102 from 1.6 µm to 1.47 µm by changing the applied voltage, and by matching the peak of the narrow bandwidth filter 101 with one of the peaks of the filter 102 by adjusting the applied voltage, the peak whose bandwidth is 8.4 GHz or 0.067 nm can be shifted from 1.6 µm to 1.47 µm.

TABLE 2

CHRACTERISTICS OF NARROW BANDWIDTH FILTER 101, WIDE TUNABLE RANGE FILTER 102 AND DOUBLE CAVITY STRUCTURE FILTER

TYPE	BANDWIDTH	TUNABLE RANGE	TRANSMITTANCE	REFLECTIVITY OF MIRRORS	GAP
1	0.07nm	12nm	35%	99%	15μm
2	3.36nm	127nm	92%	93%	6μm
3	0.067nm	127nm	30%		

NOTES: type 1: narrow bandwidth first filter 101 having two layer cavity structure as shown in Fig. 4A

type 2: wide tunable range second filter 102 having normal structure

type 3: double cavity filter of Fig. 10

As a result, as shown in Fig. 13, it was confirmed that the peak whose bandwidth is 8.4 GHz (0.067 nm) shifts by 127 nm. The transmittance was about 30%. Each peak selected is spaced 5 nm apart in this figure.

Two laser light signals, which were spaced 25 GHz (0.2nm) apart, and were modulated by a 100 MHz waveform and a 500 MHz waveform, were mixed by a coupler, and one of them was selected by the

tunable liquid crystal wavelength-selective filter of this embodiment. One of them was selected with 15 dB extinction ratio. From this, it is found that any one wave can be selected from about 600 waves (that is, about 127/0.2) by the filter of this embodiment, which is far superior to the conventional filter which can select only one wave from about 50 waves.

Next, a polarization independent photodetector employing the tunable liquid crystal wavelength-selective filter of the first embodiment is described. In this filter, the refractive index of the liquid crystal layer varies when a voltage of a few volts is applied to the liquid crystal layer because this inclines the liquid crystal molecules. As a result, the optical length between the mirrors changes, and hence, a transmission peak wavelength varies, thereby achieving the function of a tunable wavelength-selective filter as described before.

This filter, however, has this effect only on a light signal whose polarization direction is parallel to the liquid crystal molecules, and not on a light signal whose polarization direction is perpendicular to the liquid crystal molecules. This means that the filter has polarization dependence. To overcome this problem, examples using a polarization beam separation cell will be described below.

EMBODIMENT 3

Fig. 14 shows an embodiment of a polarization independent photodetector according to the present invention. In this figure, reference numeral 140 designates an input single mode optical fiber; 141, a fiber connecting portion; 142, a grin lens; 143 a birefringent prism; 144, a $\lambda/2$ plate; 145, a tunable liquid crystal wavelength-selective filter of homogeneous ordering; 146, a lens; 147, a detector made up of a PIN photodiode; 148, an electric terminal for driving the tunable liquid crystal wavelength-selective filter, and 149, an output termial of the photodetector. As the tunable liquid crystal wavelength-selective filter 145, the two layer cavity structure filter of the first embodiment, or the double cavity structure filter of the second embodiment or the conventional type filter can be used.

The ferrule of the input optical fiber 140 is inserted into the detector section along the connecting portion 141. The incident light beam is collimated by the grin lens 142, and the collimated beam is separated by the birefringent prism 143 into two polarized beams whose polarization directions are perpendicular each other. One of the two beams is directly led to the tunable liquid crystal wavelength-selective filter 145, whereas the other of them is rotated 90 degrees by the $\lambda/2$ plate 144, and then enters the filter 145 which inclines one degree with regard to the normal direction of the incident beam. Thus, although a selected optical signal transmits the filter, the other optical signals are reflected owing to the inclination of one degree, never to return to the input optical fiber 140. The two beams transmitting the filter 145 are spaced 3 mm apart, and are focused onto the detector 147 through the lens 146 with a spot diameter of 100 μm. A head portion of the PIN photodetector is 100 μm in diameter. Thus, the alignment becomes much easier than in the conventional device which has at the output side a single mode optical fiber whose core diameter is about 10 μm. In addition, the output side birefringent prism 38 and $\lambda/2$ plate 39 which are needed in the conventional device of Fig. 3 are obviated.

Fig. 15 shows the relationship between the transmission peak wavelength and the applied voltage of the tunable liquid crystal wavelength-selective filter 145 when the conventional type tunable liquid crystal wavelength-selective filter was used as a filter 145. In this measurement, a light beam produced by a DBR laser having a central wavelength at 1.5425 μm was modulated by a 1GHz signal by using an LN ($LiNO_3$) modulator, was transmitted through a 10 km long fiber, and was detected by the photodetector of this embodiment. The spectrum of the output signal was measured by varying a voltage applied to the tunable liquid crystal wavelength-selective filter 145 of the photodetector. Fig. 16A shows the result: the output beam was obtained when the voltage corresponding to the 1.5425 μm wavelength was applied. The detected output did not change when the polarization state in the fiber was changed, which means that the device is polarization independent. Fig. 16B shows a waveform of the detected output. Although the output is distorted to some extent, the correct 1 GHz signal can be reproduced.

Although the birefringent prism 143 is used as the polarization beam separation cell in this embodiment, other polarization beam separation cell can be used.

Fig. 17A illustrates one example. In this figure, the input beam is separated into two beams by a polarization beam splitter 171 and a prism 172. One of them passes a $\lambda/2$ plate 144, and thus, the polarization directions of the two beams are made parallel to the liquid crystal molecules. This arrangement achieve similar effect to that of the embodiment as shown in Fig. 14.

Fig. 17B shows another variation of the above embodiment. Although the photodetector of Fig. 14 directly receives the output beam with the detector 147, the photodetector of Fig. 17B receives the output beam with the detector 147 via a multimode fiber 175 whose core diameter is greater than 100 μm. This

photodetector can achieve similar effect as that of Fig. 14.

Next, the characteristics of the polarization independent photodetector will be explained. The tunable wavelength-selective filter used in the experiment was a narrow bandwidth filter of the first embodiment as shown in Fig. 4A. First, the transmission spectrum was measured by the set up as shown in Fig. 17A where the output beam was transmitted to the detector 147. As a result, two transmission spectra appeared. This corresponds to the fact that the light beams pass two different points in the tunable liquid crystal wavelength-selective filter. Voltages applied to the transparent electrode which is divided into two parts as shown in Fig. 17A were adjusted by controlling the variable resistor 174 so that the two transmission peaks agreed. The ratio V_1/V_2 of the two voltages was 0.98. The detector 147 directly received the output beam, and the output of the detector 147 was measured with rotating the plane of polarization of the incident beam. Fig. 18 shows the results. The transmittance little changes when the plane of polarization of the incident beam is rotated, which means that the polarization independence can be achieved by the arrangement of this embodiment. The total loss of the photodetector was 5 dB, and the loss of the portion other than the tunable liquid crystal wavelength-selective filter 145 was 1 dB. The polarization dependence of the loss was less than 0.5 dB. The filter 145 can be replaced with a conventional tunable liquid crystal wavelength-selective filter or the double cavity liquid crystal filter of the second embodiment.

EMBODIMENT 4

Fig. 19 is a block diagram showing another embodiment of the polarization independent photodetector of the present invention. In this figure, reference numeral 191 designates a stripe-like mirror; 192, a $\lambda/4$ plate; 193, a voltage source for driving the tunable liquid crystal wavelength-selective filter 145.

A light beam incident with some angle (~ 1°) onto the tunable liquid crystal wavelength-selective filter 145 passes the filter 145 if its polarization plane is parallel to the liquid crystal molecules and its wavelength is equal to the resonance wavelength of the filter 145. On the other hand, a light beam whose polarization plane is perpendicular to the liquid crystal molecules is reflected by the filter 145. The reflected light is incident onto the $\lambda/4$ plate 192, reflected by the mirror 191, transmitted again through the $\lambda/4$ plate 192, and incident again onto the tunable liquid crystal wavelength-selective filter 145. In the course of this, the light beam passes the $\lambda/4$ plate 192 twice, which is equivalent to passing the $\lambda/2$ plate. Thus, the polarization plane of the light beam rotates by 90 degrees. As a result, the polarization direction of the light beam becomes parallel to the liquid crystal molecules when the light beam enters the tunable liquid crystal wavelength-selective filter 145 again. Accordingly, the beam passes the filter 145 without reflection. Thus, the tunable liquid crystal wavelength-selective filter 145 is made polarization independent. The polarization dependence of the loss was less than 0.5 dB. In this case, since the light beam incident again onto the filter 145 is reflected in an oblique direction from the filter 145, the reflected beam does not enter the input optical fiber 140 again.

According to this embodiment, a simple, polarization independent module can be realized by only disposing a collimating lens 142, the $\lambda/4$ plate 192 and mirror 191 at the input side, and a lens 146 at the output side. In addition, since a detector 147 of 100 μm in diameter is disposed at the output side, alignment becomes very simple. Further, the detector 147 can be connected via a multimode optical fiber of the same diameter as that of the detector 147, achieving a similar effect.

EMBODIMENT 5

Fig. 20 shows still another embodiment of a polarization independent photodetector according to the present invention. In this figure, reference numeral 201 designates a single mode optical fiber; 202, a collimating lens; 203, a polarization beam splitter; 204, a prism; 205, a $\lambda/2$ plate; 206, a glass substrate; 207, transparent electrodes; 208, dielectric mirrors; 209, alignment layers for liquid crystal; 210, liquid crystal; 211, a photodetector part; 212, spacers; 213, a ground terminal; 214, a detector output terminal; 215, a terminal for driving the liquid crystal filter; and 216, a transparent glass plate.

Figs. 21A and 21B shows the photodetector part 211 in more detail. Fig. 21A is a cross-sectional view of the photodetector part 211 which comprises two GaInAs PIN photodiodes 222 on a semi-insulating InP substrate 221. Reference numeral 207 denotes a transparent electrode; 208, a dielectric mirror; 216, a transparent glass plate; and 209, an alignment layer for the liquid crystal. Fig. 21B is a perspective view of the photodetector 211. In this figure, reference numeral 223 denotes flip chip bumps connected to the photodiodes 222, and 230 denotes a flip chip bump for supplying voltage to the ITO (a ground state).

As shown in Fig. 21C, a ground electrode 227 and detector output electrodes 228 are patterned on a glass substrate 229, and are connected to the bumps. The glass substrate 229 and the glass substrate 206,

on which the dielectric mirrors 208, liquid crystal alignment layers 209 are formed, are bonded via the spacers 212 to form a Fabry-Perot etalon which includes a cavity retaining liquid crystal at the bottom side of the photodetectors 222. Thus, beams passing the Fabry-Perot etalon are incident onto the bottoms of the PIN photodiodes 222 constituting the photodetector part 211: the two polarized beams perpendicular each other are incident onto the bottoms of the two PIN photodiodes 222, and the outputs of the diodes are connected in parallel so that the device of Fig. 20 functions as a polarization independent detector.

The present invention has been described in detail with respect to various embodiments, and it will now be apparent from the foregoing to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and it is the intention, therefore, in the appended claims to cover all such changes and modifications as fall within the true spirit of the invention.

A tunable wavelength-selective filter including a glass substrate (48A), a transparent electrode layer (45A), a high reflective mirror (44A), an alignment layer (43A), a liquid crystal layer (41), an alignment layer (43B), a transparent material layer (42) whose refractivity index is substantially equal to that of the liquid crystal layer (41), a high reflective mirror (44B), a transparent electrode layer (45B), and a glass substrate (48B), which are stacked in this order. An etalon cavity of the filter includes two layers, the liquid crystal layer (41) and the glass plate (42) as a transparent material layer, which enables to lengthen the cavity length without increasing absorption and scattering of the cavity. This makes it possible to narrow FWHM, quicken the response time, and increase the transmittance of the filter. As applications of the filter, a double cavity structure tunable wavelength-selective filter of a wide tunable range, and a photodetector of a simple construction can be realized.

Claims

1. An electrically tunable wavelength-selective filter characterized by comprising:
    a first glass substrate;
    a first transparent electrode layer;
    a first high reflective mirror;
    a first alignment layer;
    a liquid crystal layer;
    a second alignment layer;
    a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of said liquid crystal layer;
    a second high reflective mirror;
    a second transparent electrode layer; and
    a second glass substrate;
    which are arranged in this sequence.

2. An electrically tunable wavelength-selective filter as claimed in claim 1, characterized in that said transparent material layer is a glass plate.

3. An electrically tunable wavelength-selective filter as claimed in claim 2, characterized in that a thickness d_1 of said liquid crystal layer and a thickness d_2 of said glass plate satisfy a condition that a ratio d_2/d_1 falls in a range from 0.8A to 1.2A inclusive, where
    A = $0.75(n_e - n_o)m/n_e - 1$,
    m = $2n_e(d_1 + d_2)/\lambda m$,
    n_e is an extraordinary refractive index of said liquid crystal,
    n_o is an ordinary refractive index of said liquid crystal, and
    λm is a transmission peak wavelength.

4. An electrically tunable wavelength-selective filter as claimed in claim 1, characterized in that said transparent material layer is an organic polymer layer.

5. An electrically tunable wavelength-selective filter as claimed in claim 4, characterized in that a thickness d_1 of said liquid crystal layer and a thickness d_2 of said organic polymer layer satisfy a condition that a ratio d_2/d_1 falls in a range from 0.8A to 1.2A inclusive, where
    A = $0.75(n_e - n_o)m/n_e - 1$,
    m = $2n_e(d_1 + d_2)/\lambda m$,
    n_e is an extraordinary refractive index of said liquid crystal,

n_o is an ordinary refractive index of said liquid crystal, and
λm is a transmission peak wavelength.

6. An electrically tunable wavelength-selective filter characterized by comprising:
a first tunable liquid crystal wavelength-selective filter; and
a second tunable liquid crystal wavelength-selective filter which is stacked on said first tunable liquid crystal wavelength-selective filter;
said first tunable liquid crystal wavelength-selective filter including:
a first glass substrate;
a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a first liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of said liquid crystal layer;
a second high reflective mirror;
a second transparent electrode layer; and
a second glass substrate;
which are arranged in this sequence,
and said second tunable liquid crystal wavelength-selective filter including:
a third glass substrate;
a third transparent electrode layer;
a third high reflective mirror;
a third alignment layer;
a second liquid crystal layer;
a fourth alignment layer;
a fourth high reflective mirror;
a fourth transparent electrode layer; and
a fourth glass substrate;
which are arranged in this sequence.

7. An electrically tunable wavelength-selective filter as claimed in claim 6, characterized in that said transparent material layer is a glass plate.

8. An electrically tunable wavelength-selective filter as claimed in claim 6, characterized in that said first tunable liquid crystal wavelength-selective filter and said second tunable liquid crystal wavelength-selective filter are stacked in such a manner that they are inclined each other.

9. An electrically tunable wavelength-selective filter as claimed in claim 6, characterized in that said transparent material layer is an organic polymer layer.

10. An electrically tunable wavelength-selective filter as claimed in claim 9, characterized in that said first tunable liquid crystal wavelength-selective filter and said second tunable liquid crystal wavelength-selective filter are stacked in such a manner that they are inclined each other.

11. An electrically tunable wavelength-selective filter as claimed in claim 6, characterized in that said first tunable liquid crystal wavelength-selective filter has a longer cavity gap than said second tunable liquid crystal wavelength-selective filter.

12. A photodetector characterized by comprising:
an input optical fiber;
lensing means for collimating light transmitted through said input optical fiber;
a fiber connecting portion connecting said input optical fiber to said lensing means;
polarization beam separation means for polarization separating said light transmitted through said lensing means into a first polarization light beam and a second polarization light beam;
polarization rotation means for rotating polarization of said second polarization light beam;
an electrically tunable liquid crystal wavelength-selective filter selectively transmitting said first and

second polarization light beams;

a focusing lensing means for focusing said first and second polarization light beams transmitted through said electrically tunable liquid crystal wavelength-selective filter; and

photodetecting means for detecting said first and second polarization light beams focused by said focusing lensing means,

wherein said electrically tunable liquid crystal wavelength-selective filter includes:

a first glass substrate;

a first transparent electrode layer;

a first high reflective mirror;

a first alignment layer;

a liquid crystal layer;

a second alignment layer;

a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of said liquid crystal layer;

a second high reflective mirror;

a second transparent electrode layer; and

a second glass substrate;

which are arranged in this sequence.

13. A photodetector as claimed in claim 12, characterized in that said polarization rotation means is a $\lambda/2$ plate.

14. A photodetector as claimed in claim 12, characterized in that said polarization rotation means is a $\lambda/4$ plate and a mirror.

15. A photodetector as claimed in claim 12, characterized in that said polarization beam separation means comprises a polarization beam splitter and a prism.

16. A photodetector as claimed in claim 12, characterized in that said polarization beam separation means is a birefringent plate.

17. A photodetector as claimed in claim 12, characterized in that said polarization beam separation means inclines the incident beam with regard to said tunable liquid crystal wavelength-selective filter.

18. A photodetector as claimed in claim 12, characterized in that said photodetecting means is a PIN photodiode or an avalanche photodiode.

19. A photodetector as claimed in claim 12, further characterized by comprising a multimode optical fiber disposed between said focusing lensing means and said photodetecting means.

20. A photodetector characterized by comprising:

an input optical fiber;

lensing means for collimating light transmitted through said input optical fiber;

a fiber connecting portion connecting said input optical fiber to said lensing means;

polarization beam separation means for polarization separating said light transmitted through said lensing means into a first polarization light beam and a second polarization light beam;

polarization rotation means for rotating polarization of said second polarization light beam;

an electrically tunable liquid crystal wavelength-selective filter selectively transmitting said first and second polarization light beams;

a focusing lensing means for focusing said first and second polarization light beams transmitted through said electrically tunable liquid crystal wavelength-selective filter; and

photodetecting means for detecting said first and second polarization light beams focused by said focusing lensing means;

wherein said electrically tunable liquid crystal wavelength-selective filter includes:

a first tunable liquid crystal wavelength-selective filter; and

a second tunable liquid crystal wavelength-selective filter which is stacked on said first tunable liquid crystal wavelength-selective filter,

said first tunable liquid crystal wavelength-selective filter including:

a first glass substrate;
a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a first liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of said liquid crystal layer;
a second high reflective mirror;
a second transparent electrode layer; and
a second glass substrate;
which are arranged in this sequence,
and said second tunable liquid crystal wavelength-selective filter including:
a third glass substrate;
a third transparent electrode layer;
a third high reflective mirror;
a third alignment layer;
a second liquid crystal layer;
a fourth alignment layer;
a fourth high reflective mirror;
a fourth transparent electrode layer; and
a fourth glass substrate;
which are arranged in this sequence.

21. A photodetector characterized by comprising: an input optical fiber;
lensing means for collimating light transmitted through said input optical fiber;
a fiber connecting portion connecting said input optical fiber to said lensing means;
polarization beam separation means for polarization separating said light transmitted through said lensing means into a first polarization light beam and a second polarization light beam;
polarization rotation means for rotating polarization of said second polarization light beam;
an electrically tunable liquid crystal wavelength-selective filter selectively transmits said first and second polarization light beams; and
at least two photodiodes independently detecting said first and second polarization light beams transmitted said electrically tunable liquid crystal wavelength-selective filter;
wherein said electrically tunable liquid crystal wavelength-selective filter includes:
a first glass substrate;
a first transparent electrode layer;
a first high reflective mirror;
a first alignment layer;
a liquid crystal layer;
a second alignment layer;
a transparent material layer whose refractive index is substantially equal to that of a liquid crystal of said liquid crystal layer;
a second high reflective mirror; and
a second transparent electrode layer,
which are arranged in this sequence, wherein said electrically tunable liquid crystal wavelength-selective filter and said photodiodes are integrally arranged in such a manner that said photodiodes are arranged on said second transparent electrode layer.

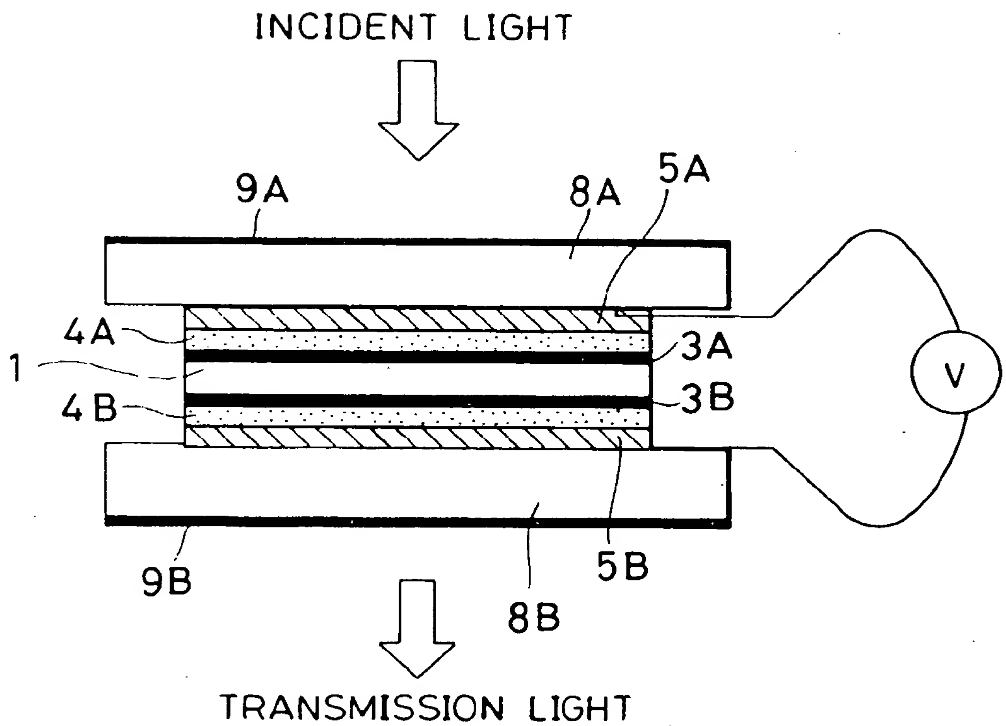

FIG.1
(PRIOR ART)

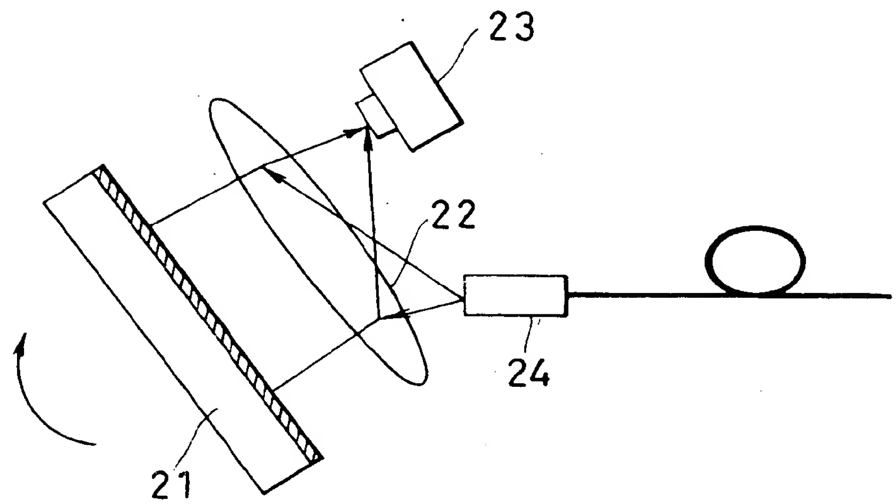

FIG.2
(PRIOR ART)

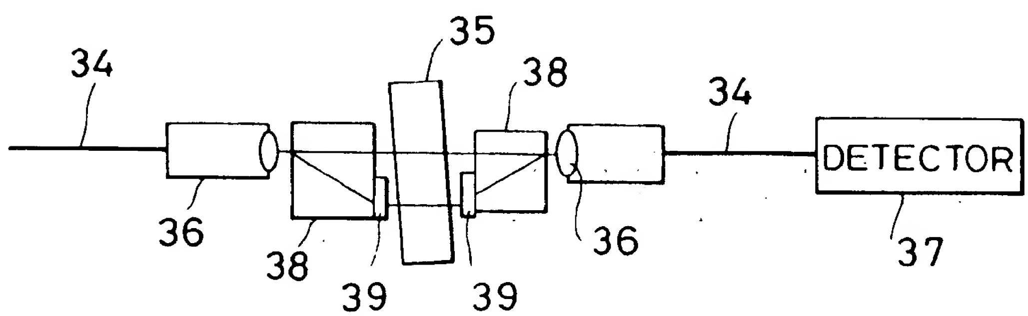

FIG.3
(PRIOR ART)

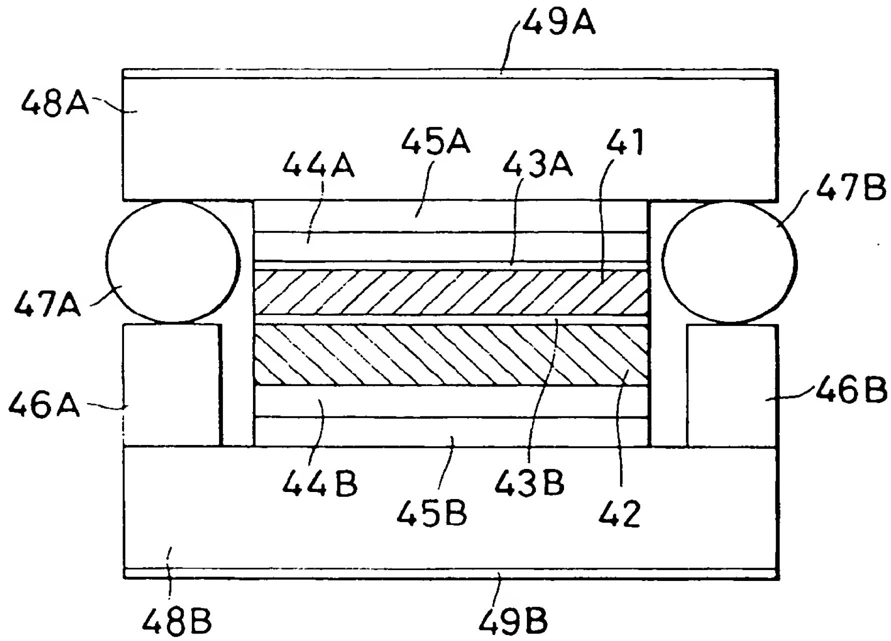
49A
48A
44A
45A
43A
41
47B
47A
46A
46B
44B
45B
43B
42
48B
49B

FIG.4A

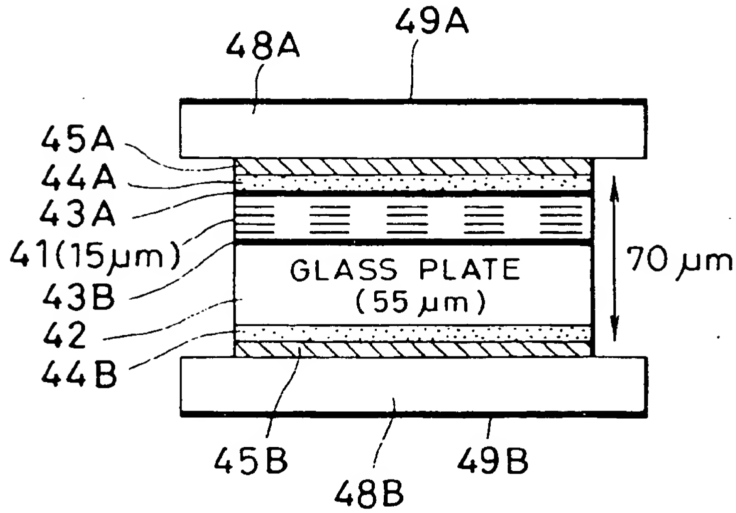
48A
49A
45A
44A
43A
41(15µm)
43B
42
44B
GLASS PLATE
(55 µm)
70 µm
45B
48B
49B

FIG.4B

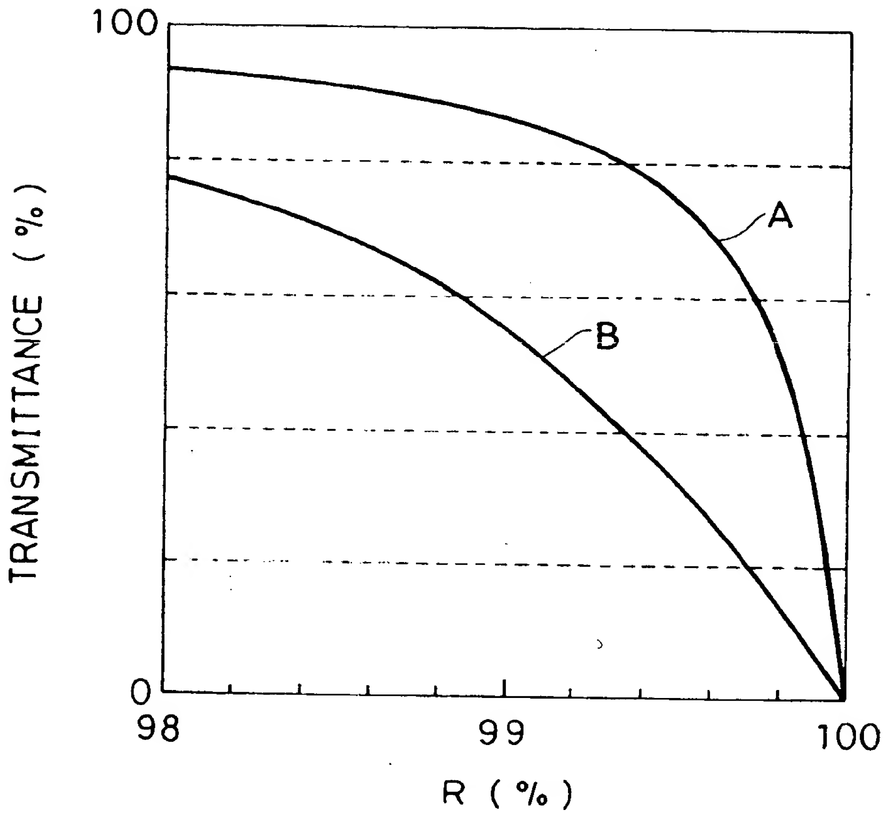

FIG.5

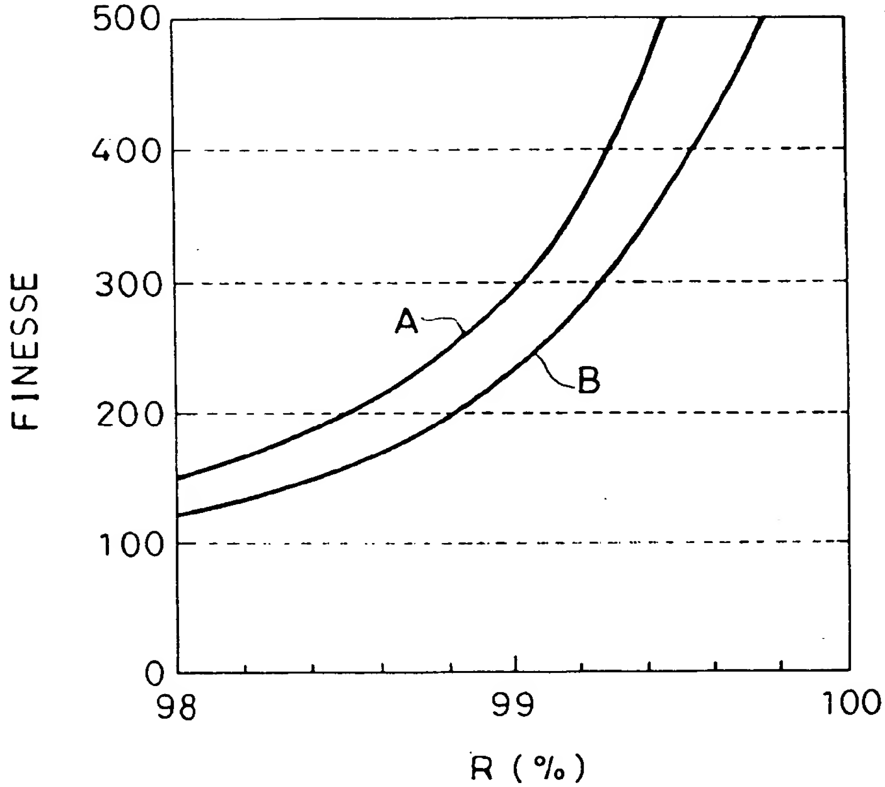

FIG.6

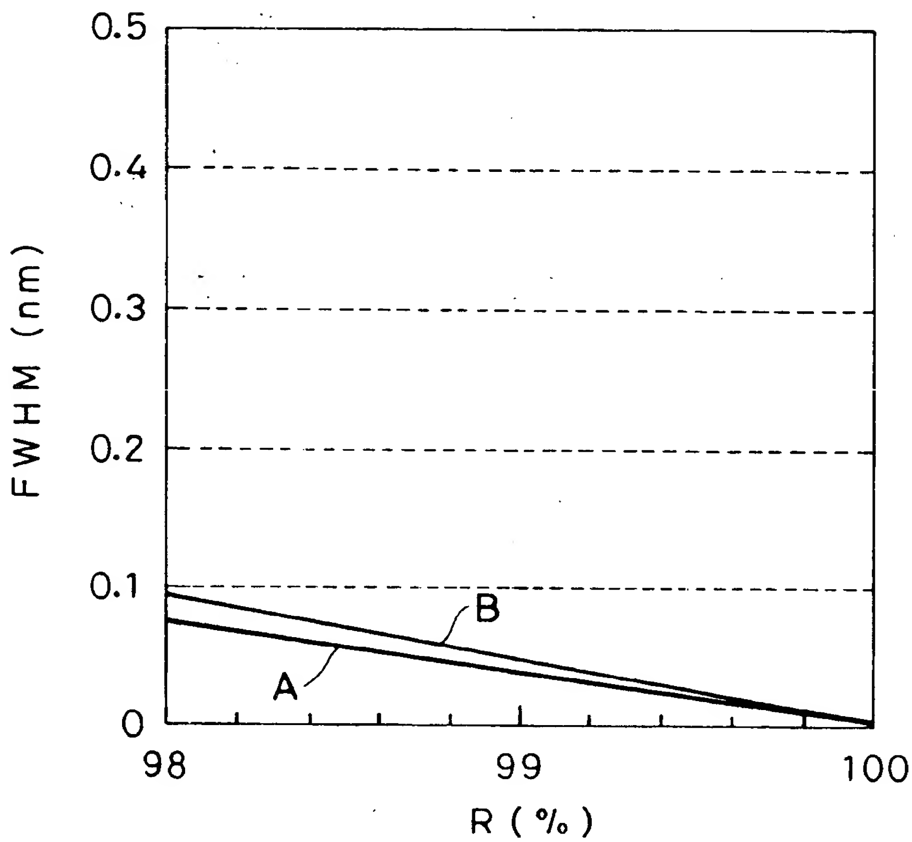

FIG.7

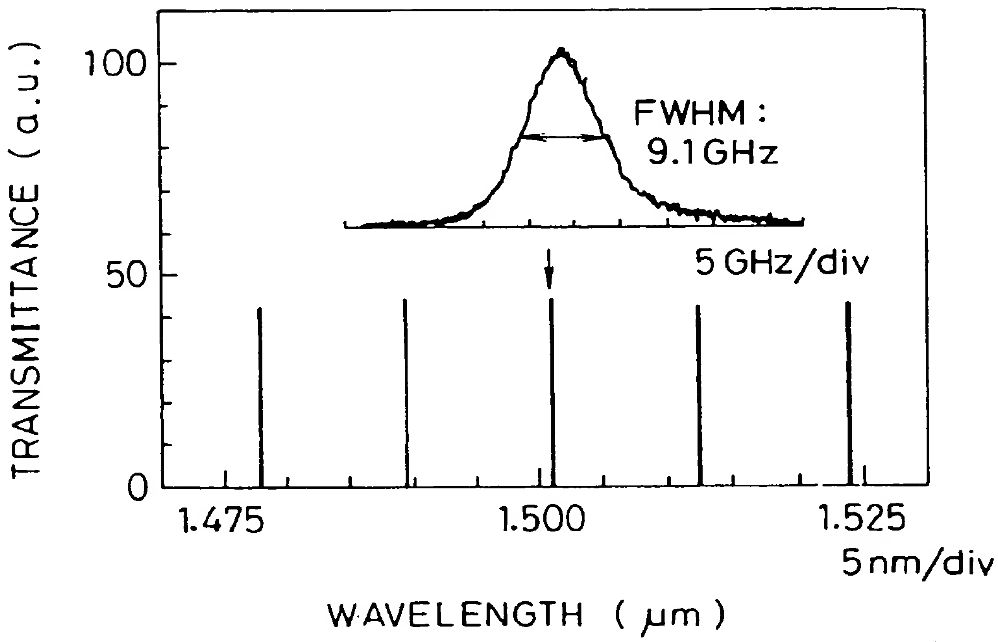
TRANSMITTANCE (a.u.)
100
50
0
FWHM :
9.1GHz
5 GHz/div
1.475
1.500
1.525
5nm/div
WAVELENGTH (μm)

FIG.8

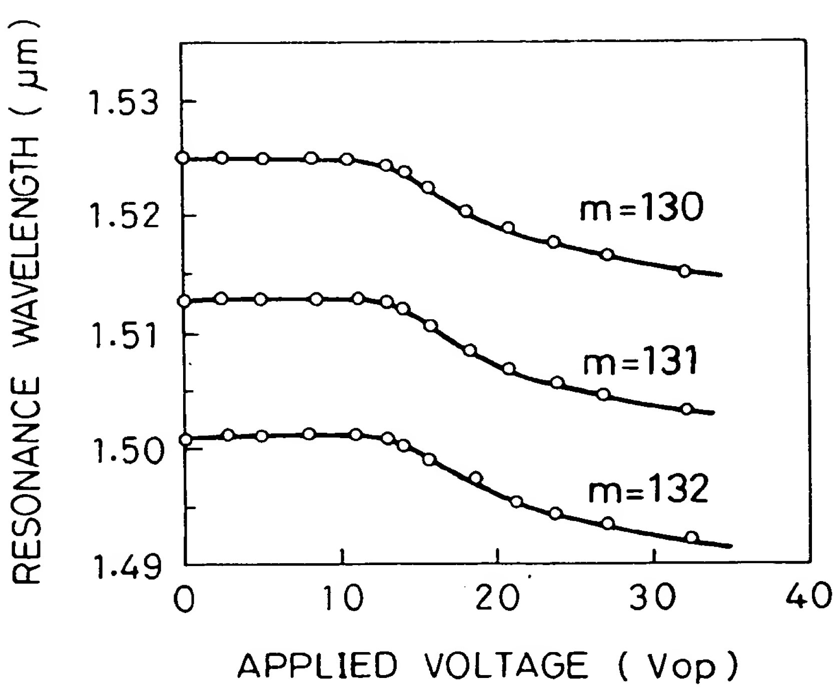
RESONANCE WAVELENGTH (μm)
1.53
1.52
1.51
1.50
1.49
m=130
m=131
m=132
0
10
20
30
40
APPLIED VOLTAGE (Vop)

FIG.9

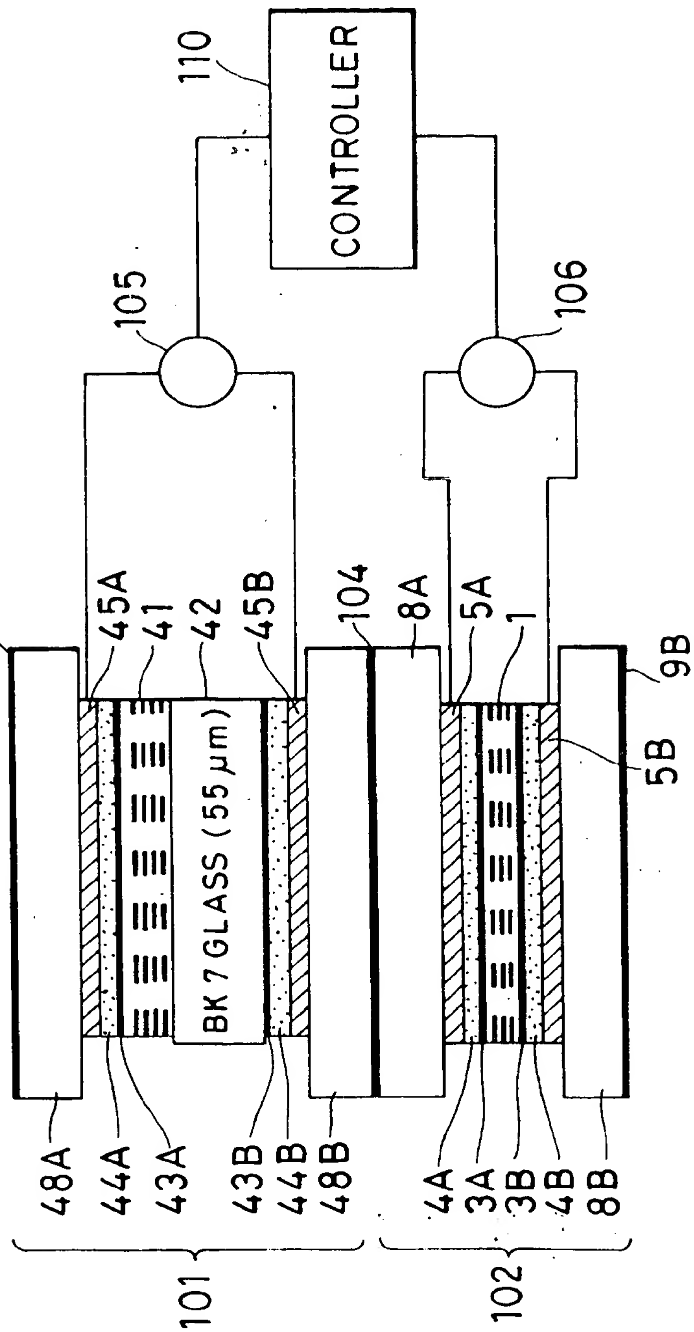
CONTROLLER
110
105
106
49A
45A
41
42
45B
104
8A
5A
1
9B
5B
BK 7 GLASS (55 μm)
48A
44A
43A
43B
44B
48B
4A
3A
3B
4B
8B
101
102

FIG. 10

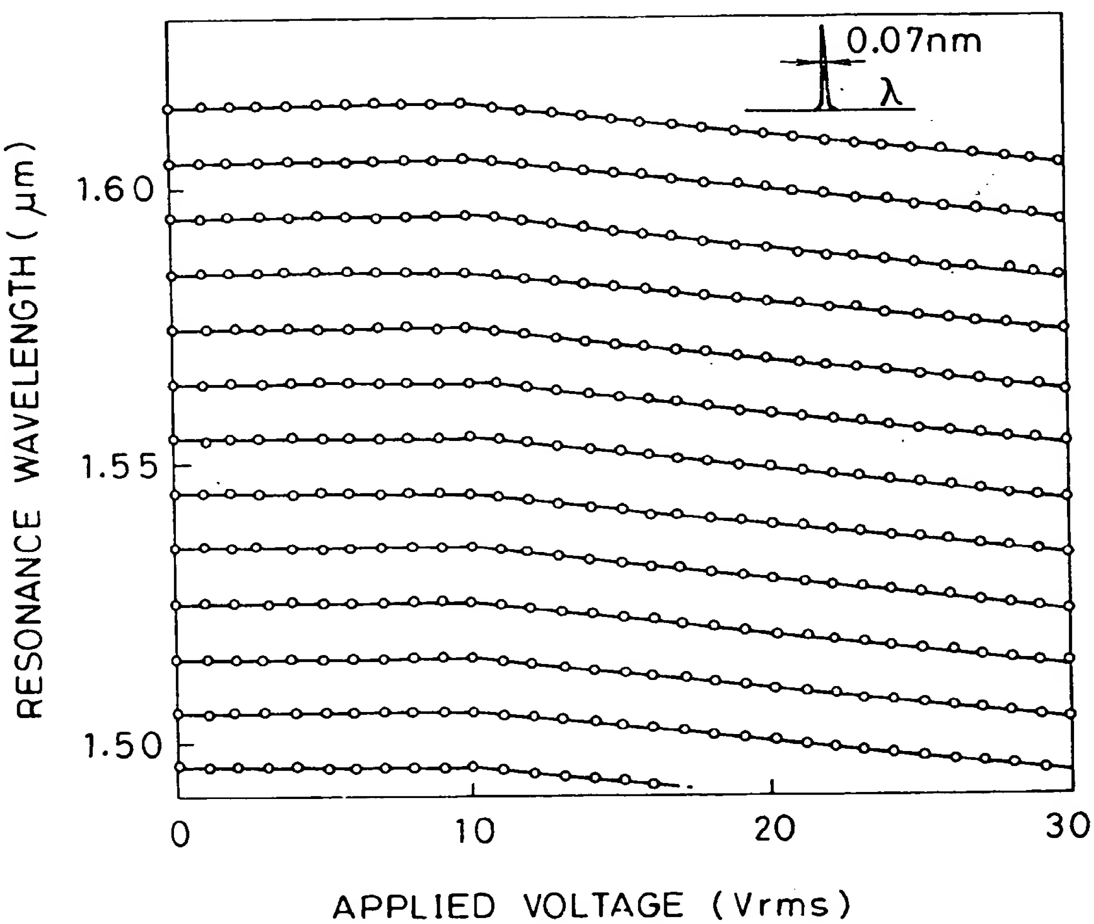
0.07nm
λ
RESONANCE WAVELENGTH (μm)
1.60
1.55
1.50
0
10
20
30
APPLIED VOLTAGE (Vrms)

FIG.11

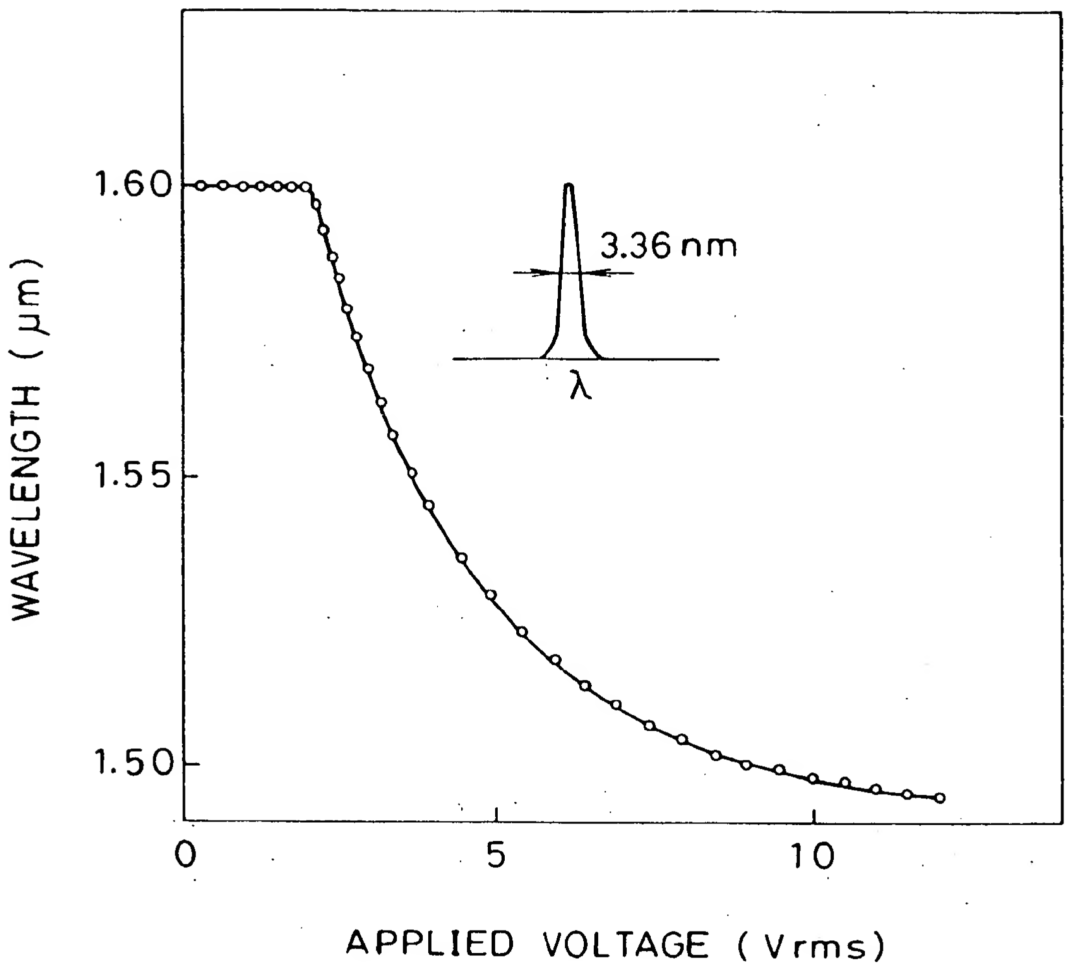

FIG.12

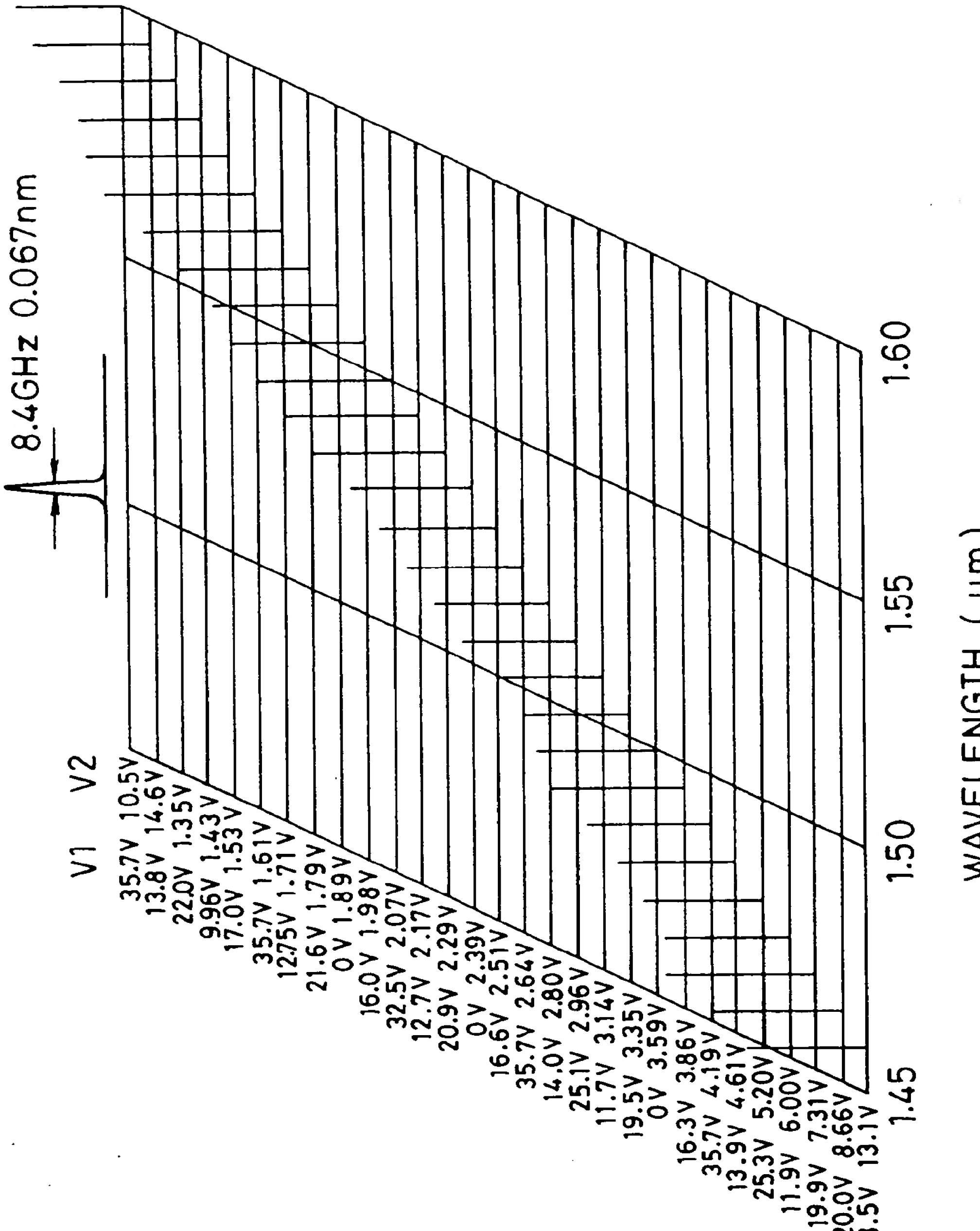
8.4GHz 0.067nm
V1 V2
35.7V 10.5V
13.8V 14.6V
22.0V 1.35V
9.96V 1.43V
17.0V 1.53V
35.7V 1.61V
12.75V 1.71V
21.6V 1.79V
0V 1.89V
16.0V 1.98V
32.5V 2.07V
12.7V 2.17V
20.9V 2.29V
0V 2.39V
16.6V 2.51V
35.7V 2.64V
14.0V 2.80V
25.1V 2.96V
11.7V 3.14V
19.5V 3.35V
0V 3.59V
16.3V 3.86V
35.7V 4.19V
13.9V 4.61V
25.3V 5.20V
11.9V 6.00V
19.9V 7.31V
20.0V 8.66V
18.5V 13.1V
1.45
1.50
1.55
1.60
WAVELENGTH (μm)

FIG.13

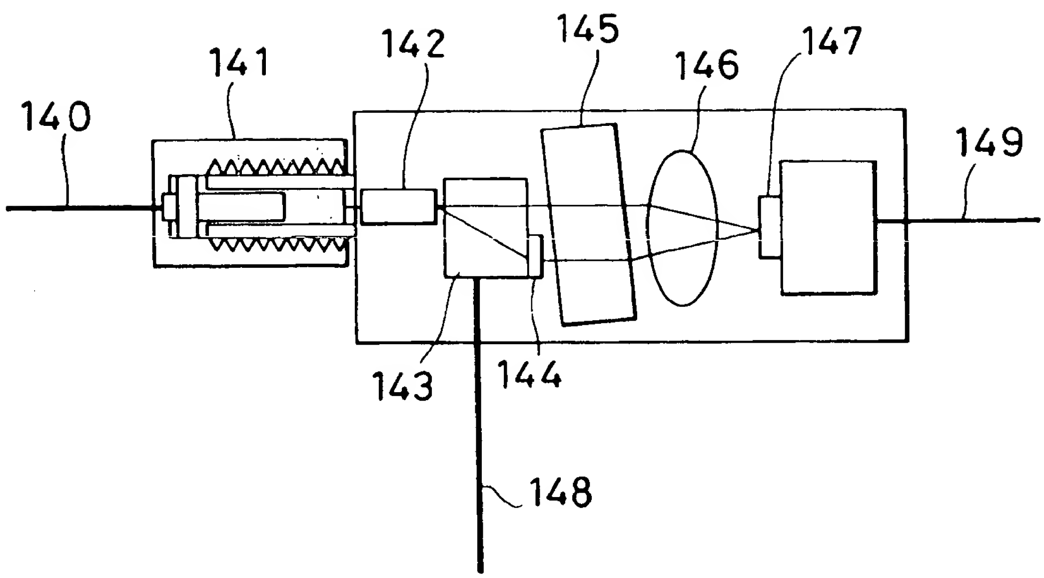

FIG.14

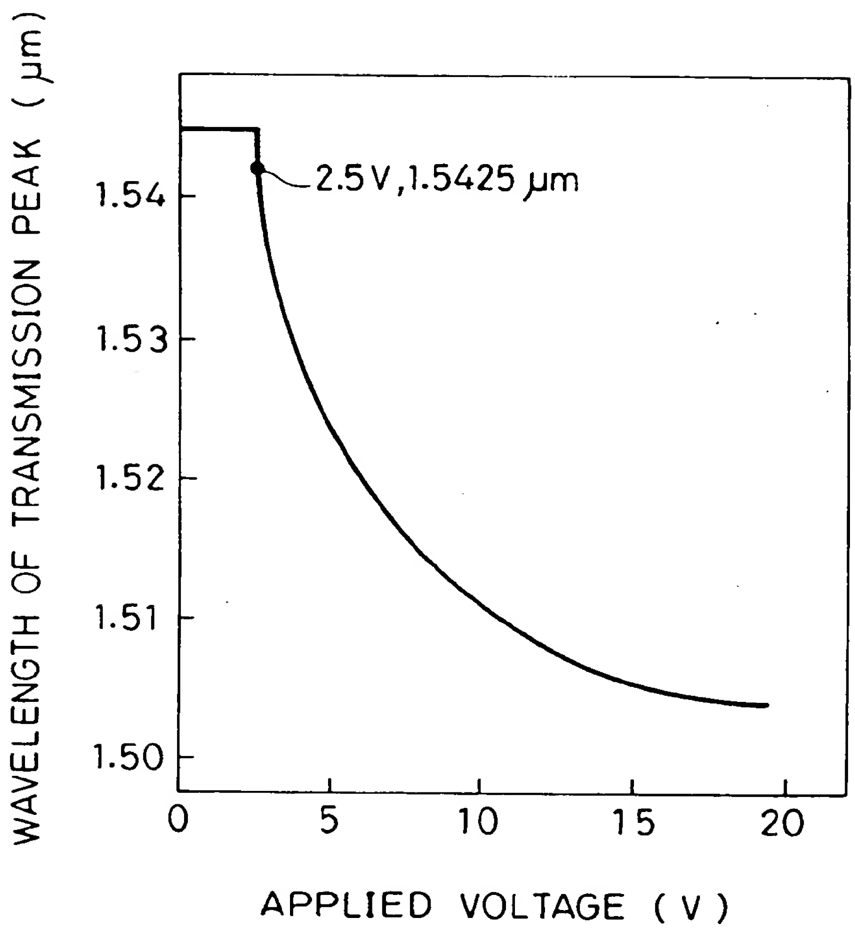
WAVELENGTH OF TRANSMISSION PEAK (μm)
1.54
1.53
1.52
1.51
1.50
2.5V,1.5425 μm
0
5
10
15
20
APPLIED VOLTAGE (V)

FIG.15

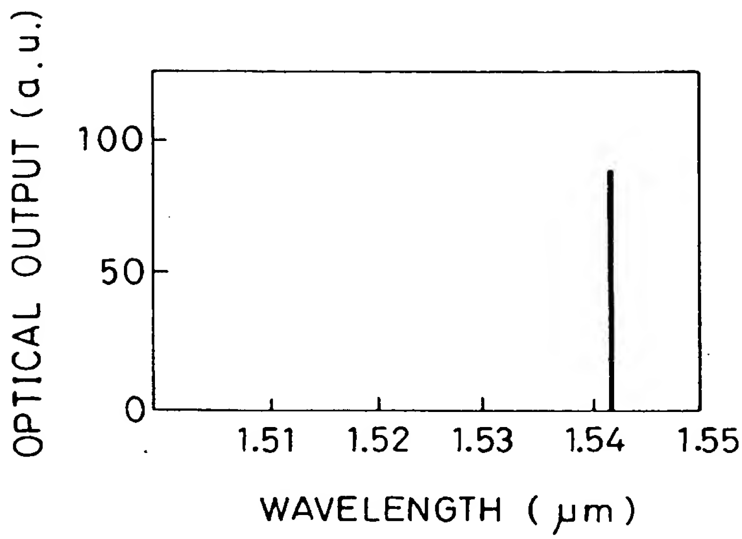

FIG.16A

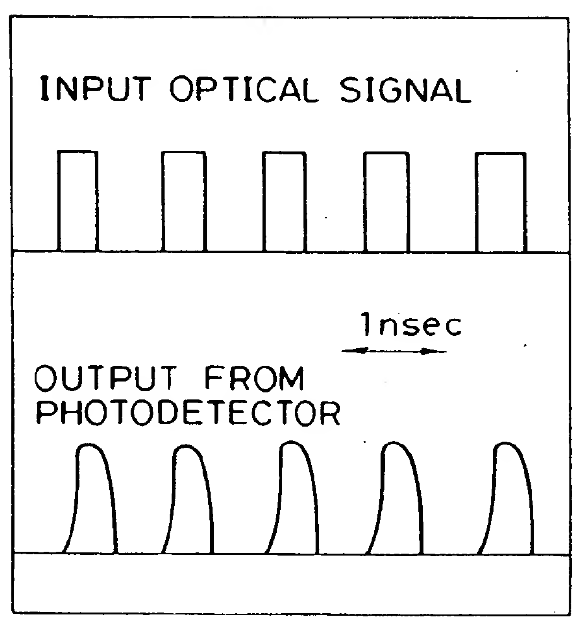

FIG.16B

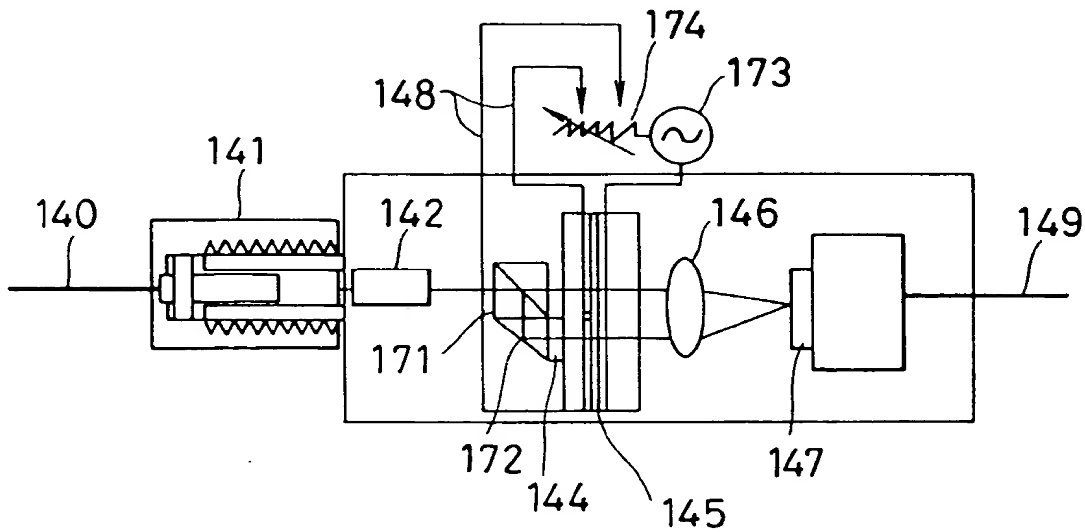

FIG.17A

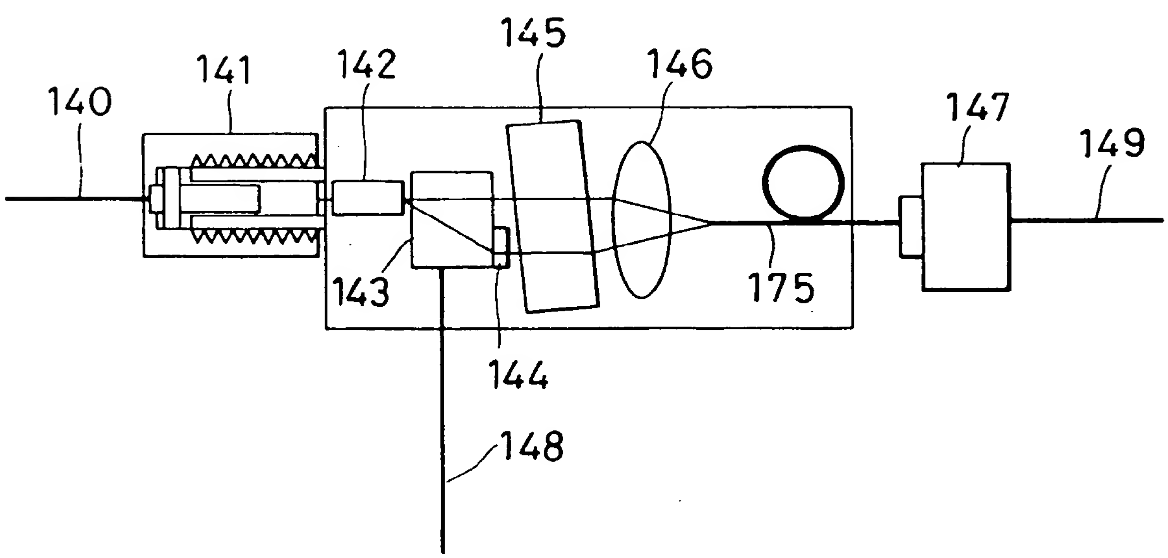

FIG.17B

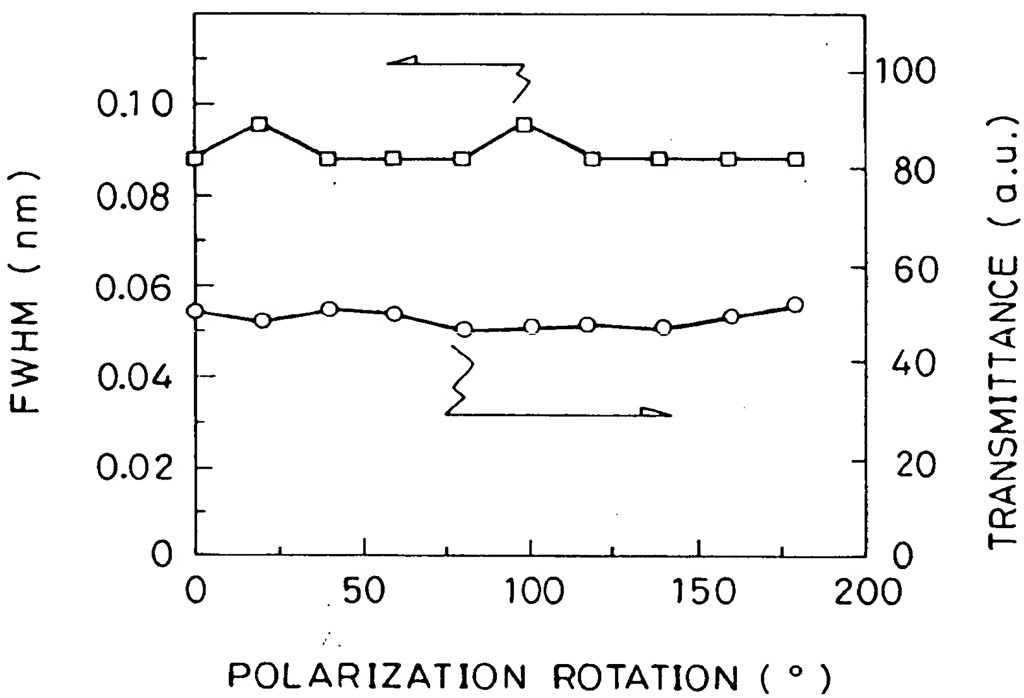
0.10
0.08
0.06
0.04
0.02
0
100
80
60
40
20
0
0
50
100
150
200
FWHM (nm)
TRANSMITTANCE (a.u.)
POLARIZATION ROTATION (°)

FIG.18

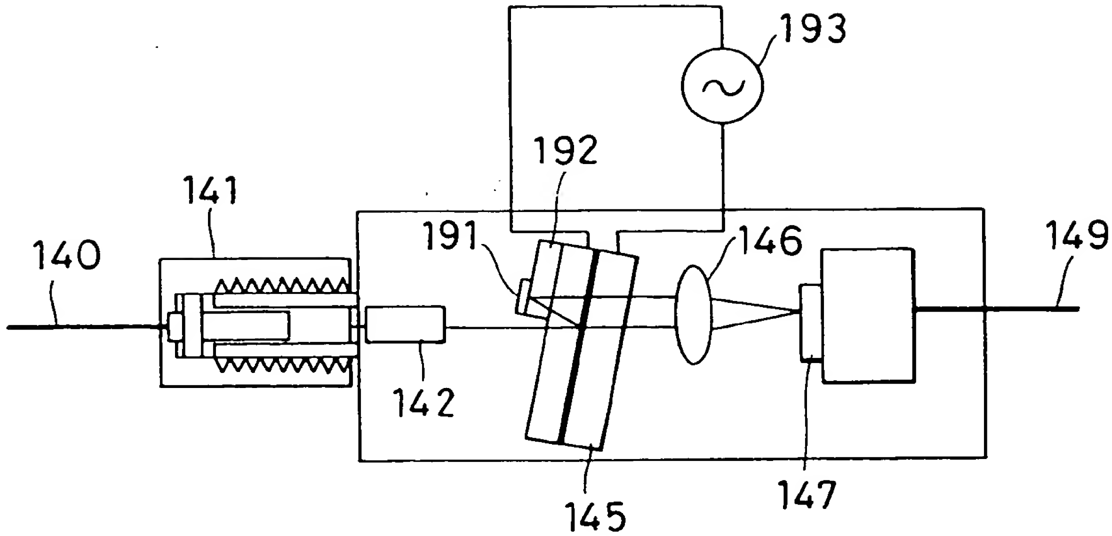
193
192
141
191
146
140
149
142
145
147

FIG.19

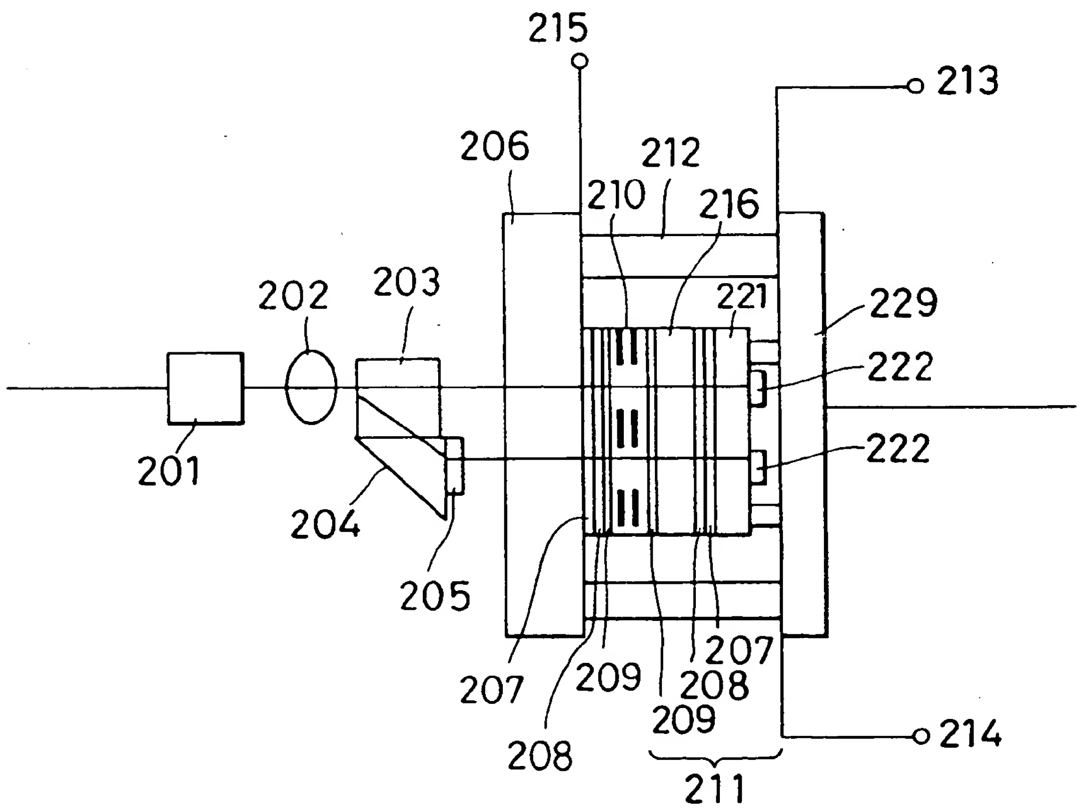
215
213
206
212
210
216
203
202
221
229
222
222
201
204
205
207
209
207
208
207
209
208
208
209
214
211

FIG.20

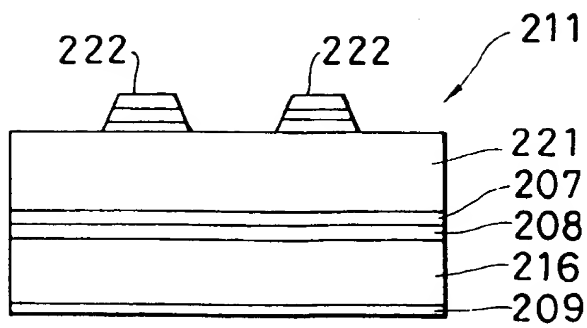

FIG.21A

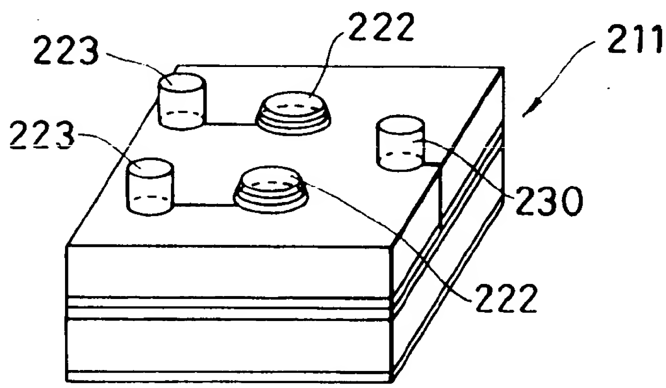

FIG.21B

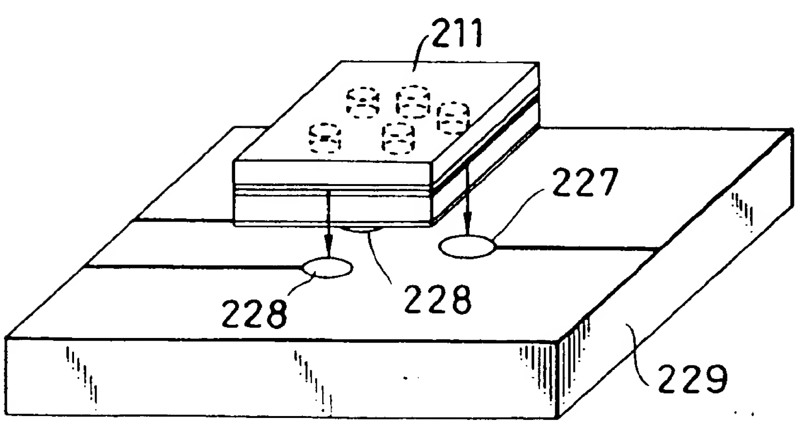

FIG.21C

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 92101834.7

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	GB - A - 2 219 099 (STC PLC) * Page 1, lines 1-17; page 3, line 1 - page 4, line 30; fig. 2,4,5 *	1,6, 12,19, 20,21	G 02 F 1/21 G 02 F 1/1333 H 01 S 3/106
A	GB - A - 2 222 464 (GEC MARCONI) * Page 3, line 16 - page 8, line 15 *	1,6, 12,20, 21	
A	EP - A - 0 384 117 (IBM) * Abstract; fig. 1,3 *	6,20, 21	
A	US - A - 4 779 959 (SAUNDERS) * Column 4, line 48 - column 7, line 2 *	1,6, 12,20, 21	
			TECHNICAL FIELDS SEARCHED (Int. Cl.5)
			G 02 F 1/00 G 02 F 2/00 H 01 S 3/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	14-05-1992	GRONAU

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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